FINAL REPORT TO

THE NATIONAL CENTER FOR PRESERVATION TECHNOLOGY AND TRAINING

Development and testing of a next-generation micro-fading tester for non-destructive lightfastness evaluation of art and artifacts

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EXECUTIVE SUMMARY

This project was part of a continuing effort to further develop the fading tester, a device that permits assessment of the light sensitivity of a colored artifact. In this work we have evaluated the currently available commercial fiberoptic spectrometers, which form the detector for the color change measurements performed by the tester. Five devices were operated and compared according to key performance features such as precision, accuracy and stability of spectra and color difference measurements. While there were slight differences in capability, they were each found to be adequate for use as detectors in the fading tester. Two of the devices had some intrinsic limitations that added artifacts to measured spectra, and this might make them somewhat less desirable options should one choose to use them for other functions besides fading test detectors. For use in fading tests that use illumination sources of low correlated color temperature, however— as would be done to assess color stability in environments lit with incandescent lamps— two of the devices were clearly poor performers, and either recorded inaccurate or very unstable spectra. Finally, the software packages that were provided with the devices were evaluated and compared for their usability in fading tester applications. In terms of its overall performance and the functionality of the controlling software, the Control Development spectrometer seems to offer overall superior performance for use as the detector in a fading tester.

INTRODUCTION: PARTNERSHIP WITH COMPANY AND ALTERED SCOPE OF CURRENT PROJECT

Five years ago scientists at the Research Center on the Materials of the Artist and Conservator at Carnegie Mellon University built a new machine, a fading tester, that made it possible to determine whether a colored material on an art object was vulnerable to light fading without causing any damage to the object. Since that time, lectures have been given to conservators and scientists, and demonstrations of the fading tester have been performed at museums, conservation schools, and professional meetings. The interest in this device has been great, for the potential to obtain such information, which is of fundamental importance in preserving objects, has never before been obtained easily and nondestructively. Many conservators at museums, libraries, archives, historical societies, and the National Park Service, have expressed interest in obtaining this instrument.

This NCPTT grant project was designed to be the next step in the development of this machine, to make it convenient, reliable, and safe, and thus ready to be commercialized. In its current form, it is still a piece of laboratory equipment requiring assembly, painstaking alignment and calibration, and tedious re-plotting of computer data. The proposed project intended to improve upon the most important of these shortcomings, the need for difficult adjustments of the lamp and focusing lens at the test head assembly.

Soon after the start of this grant activity, however, the course of this project changed. In October 1999 a company approached us and expressed interest in developing and commercializing the fading tester. That company, a world leader in light aging test equipment, agreed to work with us to coordinate the needed development efforts. Their expertise in light source technology made them the logical partner to continue that aspect of the development. We decided to redirect our project to critically examining the available fiberoptic spectrometer technology, so that two important decisions could be made: which spectrometer should be incorporated into the commercial version of the fading tester, and how much software development will be necessary in order to have a viable product. In this report we describe our progress in this effort.

SUMMARY OF TECHNICAL ACTIVITIES AND PROGRESS

I. Performance evaluation of spectrometers

When the original fading tester prototype was constructed 5 years ago, there was only one commercially available spectrometer that was fiberoptic-based and that used a photodiode array detector, a key component for stable measurement of high light intensity. Since that time, other such spectrometers have come on the market, and the original device has been superseded by another product from that manufacturer. Clearly, the further development of a commercial fading tester should incorporate the spectrometer that proves to be most suited for the purpose. The objective of this project activity then was to evaluate the five available spectrometers (as of October 2000) for their use as a fading tester detector. To do that, the criteria by which to judge and compare the different products were first developed, and each of the five products were operated and judged against those criteria.

A. Function of device and critical performance features

The basic design of the fading tester is shown schematically in Figure 1, and photos of the prototype tester are shown in Figure 2. The tester is composed of three parts: the light source, the test head optics, and the spectrometer that analyzes the light reflected from the sample. Each of the spectrometers in this evaluation was tested by incorporating it as the detector in the fading tester prototype.

The fiberoptic-based spectrometers all function in the same fundamental way. The fiber introduces a beam of light into the device, and this beam is directed onto a grating that disperses the light into its component wavelengths. The light beam, now spread into a broad spectrum, is directed onto a photodiode array, an arrangement of photodiodes that each detects one portion of the light spectrum. Electronic circuitry reads the signal from each of the photodiode elements, processes that signal, and converts it into a digital form that can be transmitted to a computer. Within the computer software, corrections can be made to adjust the observed signals for the sensitivity of the photodiodes to different wavelengths, and the spectrum of light can thus be derived, displayed, and stored.

Refinements to this basic design can improve the performance of the device. A narrow slit aperture at the entrance to the spectrometer can improve the spectral resolution, or the ability to discriminate between wavelengths. A typical problem in spectrometers is stray light, which can be from light scattering from the edges of mirrors and gratings, or reflected back from the surface of the detector. This can be addressed by minimizing the size of the light beam and by reducing the number of optical elements in the spectrometer, for instance by using a concave grating rather than a flat grating with a concave mirror.

Similar to stray scattered light is the problem arising from so-called higher order diffraction from the grating, in which the detector element intended to sense 400 nanometer light is also illuminated with 800 nanometer light due to the second-order diffraction from the grating. This is not usually a problem in the visible spectrum, where light intensities are usually much greater than at the higher wavelengths. However, for the application using low color temperature illumination, in which the light intensity at the blue end of the spectrum is very low compared to that at the red wavelengths, spurious signals at the blue wavelengths can result from second-order diffraction of the red wavelengths. A solution to this problem is to use a simple optical filter (in this case, a red-absorbing material that is painted over the elements of the diode array that will sense blue light), called an "order-sorting filter," to ensure only the desired wavelengths reach the detector element.

Beyond this common functionality, there are many differences in design and performance that will distinguish particular products. Components in the optical system (number of lines in the grating, ruled or holographic grating, number of elements in the diode array, and slit size, if any) will affect spectral resolution. Size of fiber/slit and detector sensitivity will affect noise and stability, dynamic range, and integration time (the time during which the diode elements are allowed to collect light before a signal is read from them). For color fading measurements of art objects, integration times must be short in order to get rapid updating of the spectrum and current color difference during the test. The electronic circuitry that reads the signals from the detector limits the speed for spectral collection, and the bit-resolution of the analog/digital converter circuitry will affect the accuracy of the translation of the signal to the computer. Finally, the computer software, at least in its current version, will dictate how easy are the calculations of color parameters and differences, the desired ultimate results of the fading tests.

While it may seem that spectrometers could be ranked simply on the basis of these design features alone, in fact the true test of the device is how well it performs as a fading tester detector, in both the accuracy and stability of their color measurements. This is impossible to assess based on specifications alone. As a result, the devices have been compared on the basis of their specifications and on their performance as a color-measuring device (versus a commercial photodiode-based spectrophotometer) and fading test detector.

B. Comparison of manufacturers' specifications for five devices

Table 1 shows the comparison of the specifications for the five fiberoptic photodiode array spectrometers in this evaluation, according to the information provided by the manufacturers. All five cover the visible wavelength spectrum, with varying spectral resolution determined by the slit, grating, and number of elements in the diode array. All the devices, even the Data Optics device that has a relatively low wavelength resolution (reported as 9 nanometers), seem adequate for color measurements of nearly all pigments and dyes. In fact, commercial (abridged) spectrophotometers designed for color-measuring applications often have only 10 or 20 nanometer resolution.

While the grant activity was focused on the use of these devices as fading tester detectors, it is conceivable that the spectrometer might also be used as the radiometer for the illumination source, in which case the accuracy of the measured light levels might be required. In this case, the Data Optics device, which lacks an order-sorting filter to reduce spurious signal in the visible range, might be incapable of serving this function, and the devices with low resolution analog/digital converters might prove poorer performers in this application. Actual performance tests of the devices for this use were beyond the scope of the current study, however.

Other features seem to vary among the devices. The stray light figure seems to be lower for those devices having holographic gratings, but it is difficult to make precise comparisons because this stray light specification is reported differently for each manufacturer. Similarly, noise levels are reported differently, with some reporting dark noise (thermal noise in the electronics) while others report signal-to-noise, which would include both electronic noise and statistical noise on the signals. For standard fading tester applications, this noise will contribute to small random color difference fluctuations, which in turn will set a limit on the sensitivity of the fading tester. This performance limit is best evaluated in a fading test, rather than by deriving it from the noise specification, however.

C. Comparison of performance for the five spectrometers

The performance of the five spectrometers was evaluated in four ways. They were: 1) the precision and accuracy of spectral/color measurements as compared to a commercial diode-based spectrometer (Macbeth Color-Eye 7000), and the stability of the spectral measurements over time scales similar to fading tests; 2) fading test performance; 3) spectral and fading tests with low correlated color temperature illumination; and 4) evaluation of the software provided with the instrument.

1. Performance as spectrometer/colorimeter: precision, accuracy, and stability

a. Precision: Wavelength resolution, stray light, and noise level

The precision of the spectral measurements is determined in large part by the noise level on the spectrum. This noise is derived from the noise on the "dark" signal (thermal noise in the detector and electronic circuitry), the statistical noise on the light signal, and fluctuations in the lamp. The signal-to-noise can be improved by increasing the integration time (allowing the photodiode array to collect more light signal before being sampled by the electronics) and by averaging a number of spectra. The signal-to-noise can be *apparently* improved by mathematically smoothing the spectra. While some of the software allowed for smoothing the spectra, we evaluated the devices with no smoothing of the data.

Measuring the spectrum of a line source, such as a fluorescent lamp, allows the convenient evaluation of wavelength resolution and stray light, which contributes spurious signal to the wavelengths between the emission lines in the spectrum. Noise levels can also be assessed in these, or any other, measurements of reasonably intense light levels. Spectra of the visible emission from a UVA fluorescent lamp (Q-Panel UVA-351) are shown in Figure 3. For this measurement the uncorrected A/D counts were plotted as the best measure of intensity. All of the devices were able to measure the spectrum of the lamp, with noise and stray light levels that were practically zero. Two of the devices, the American Holographic and the StellarNet, showed superior wavelength resolution, with the latter device being the only one capable of resolving a pair of emission lines near 580 nm. The low resolution of the Data Optics spectrometer seems due to the dispersion of the grating and to the relatively large slit size (100μm internal fiberoptic), for the apparent wavelength resolution is about equal to the 9 nm resolution stated by the manufacturer, and much greater than the 3 nm resolution which should be provided by the 128-element photodiode array over the device's spectral range. For applications requiring greater wavelength resolution, selection of a smaller slit might improve the performance observed here. Determination of the optimum slit size for each of these devices was beyond the scope of this project.

For all of these devices, the noise and stray light levels and the wavelength resolution seem sufficient to measure reflectance spectra of pigments and dyes accurately, even under illumination with sources having low correlated color temperatures. That capability was tested in the following evaluations.

b. Accuracy of spectral measurements

Reflectance spectra measured in the fading tester geometry (0° illumination / 45° detection) were compared to those measured in a commercial abridged spectrophotometer (diffuse illumination / 0° detection) calibrated to NIST standards (hereafter termed the "standard" spectrophotometer). Reflectances of standard color tiles measured with the five devices compared with the standard spectrophotometer results are shown in Figures 4a-e. All of the devices provide spectra that are close (within 5 - 10% across the visible spectrum) to the standard instrument measurements. Deviation of the fading tester measurements from the standard are not consistent over all the different color tiles and are probably due more to differences in the measurement geometry than to intrinsic flaws in the diode array detectors. The magnitude of the discrepancies is best captured by the differences in the calculated tristimulus values XYZ and by the calculated total color differences between the spectra captured by the two devices (fading tester and standard spectrophotometer). These are compiled in Tables 2 and 3.

In this evaluation, no one device was a superior performer in measuring more accurate reflectance spectra, and there seemed to be correlations between the accuracy of the spectrum and the color tile being measured: for example, all five devices measured the brown tile reasonably accurately (within 5% across the visible range), while the green and pink tiles were measured less well by all the devices (deviations as large as 15%). This suggests that the measurement geometry of the fading tester, rather than its detector, is the more likely source of the observed discrepancies. Similar large deviations from the standard reflectance spectrum have been observed for samples having rough or textured surfaces, where the integrating sphere on the standard spectrometer is essential to capture the poorly diffused reflected light.

While none of these devices was so poor a performer that its use is unfeasible, two of the devices displayed significant irregular behavior that warrants closer scrutiny should they be considered for fading tester use. The Ocean Optics device itself seemed to operate satisfactorily, but the reflectance data were recorded with unusually low precision (only three significant figures). This did not severely compromise ordinary reflectance spectra, which were recorded at 0.1% precision, but when highly reflecting or fluorescent colors were measured, the reflectances above 100% were only recorded at 1% precision and resulted in severe pixellation of the spectrum at those high reflectances. The appearance of that distortion is shown in Figure 5. In fairness, this version of the controlling software is a new release, and such a problem may be remedied in later versions.

On the other hand, the StellarNet device seems to suffer from a problem that may not be so easily corrected with software modification. For this device, the spectrum that is recorded by the detector has a slight discontinuity wherever the raw A/D count level passes a particular value (in this case, around 1600 counts). Because this discontinuity occurs at the wavelength where this count level is reached, it occurs at different wavelengths depending on the sample reflectivity. This results in irregularities, sometimes pronounced, at random positions in the spectrum. An example of this phenomenon is shown in Figure 6, which shows the artifacts produced at 480 nm and 620 nm for that sample. According to the manufacturer, this is a common problem with their device that cannot be repaired or resolved by replacing it, and the only solution to removing the spectral artifacts was to smooth the spectrum mathematically. Since it is likely that users would be unwilling to examine the spectra at such length to determine whether such features are artifacts, it seems more reasonable to judge the StellarNet device a poorer choice based on its introduction of artifacts into the spectrum.

c. Accuracy of color difference measurements

The previous evaluation suggests that, probably due to non-standard measuring geometry, spectral measurements in fading tests are not being accurately recorded. For fading tester applications, though, the accuracy of measured color *differences* is more important than the absolute accuracy of the spectral measurements themselves. That is to say, the accuracy of the spectrum itself is less important than the accurate recording of changes to that spectrum as fading proceeds.

In a previous evaluation of the first prototype (Whitmore et al. 2000), a method was developed for assessing the accuracy of these measured color differences. Measurements were made on pairs of Munsell color chips in the fading tester and in the standard spectrometer. This type of sample— having a smooth planar surface of an opaque uniform color— is most amenable to precise measurement by both the standard and non-standard geometries. The color differences calculated between the measured spectra of pairs of chips were compared and plotted in a correlation plot.

The results are shown in Figure 7. All of the devices show reasonably precise and accurate color differences between pairs of chips. The Data Optics spectrometer was the best performer, perhaps due to the relatively low resolution of the reflectance spectra it records. The American Holographic, Control Development, and StellarNet devices were precise, but tended to give slightly greater (by about 10%) color differences than the standard measurement. The Ocean Optics device did not trend higher than the standard spectrometer, but the tightness of the correlation was not as good as the other devices.

d. Stability of spectra/color difference measurements

In addition to the accuracy of measured spectra and color differences, the stability of those measurements is an essential performance feature for a fading test. Color changes caused by the instrument, either drift in the spectrometer or changes in the illumination conditions due to the lamp, determine the sensitivity of the device to fading changes in the sample. For instance, in the first prototype fading tester, the drift in the color measurements was on the order of 0.2 ΔE units per hour (Whitmore et al.

1999). This means that only samples which fade to a greater degree in an hour can be observed in a fading test.

The stability of the spectral/color measurement was examined by recording the color difference over time as the fading tester measured a standard tile whose color was known to be stable. The color differences were recorded over the first 30 minutes (called short-term tests), which is typically the maximum time when doing measurements of reasonably stable (lightfastness roughly equal to Blue Wool #3) colors with UV-free illumination. Long-term tests recorded color differences over an 8-hour period, the practical maximum length of a fading test that will not be left unattended.

The results of the stability tests for the five spectrometers are shown in Figures 8a-b. For all five devices, the short-term stability of the measurements (Fig. 8a) was very good, with overall drift of no more than about 0.1 ΔE units over 30 minutes, and fluctuations ranging from a low value of about 0.03 ΔE units (Control Development) to a high of about 0.1 ΔE units (American Holographic and StellarNet). (The apparent abrupt changes in the color differences measured with the StellarNet device were a result of its software only storing color difference values to 0.1 ΔE unit precision.) These values of drift and fluctuations are comparable to those measured for the first prototype fading tester (Whitmore et al. 1999).

The long-term stability (Fig. 8b) did show larger drift over 8 hours. The Control Development device showed very smoothly varying color differences up to about 0.4 ΔE units after 8 hours, and this is due to decreased reflectance of about 1% over this period. This change is likely due to the gradual aging of the xenon lamp source over this period, which reduces its intensity. Taking this as the gauge of intrinsic drift of the lamp, the American Holographic and Data Optics devices displayed about the same amount of drift, albeit with greater short-term fluctuations, and the Ocean Optics and StellarNet devices showed larger changes of about 0.8 ΔE units over 8 hours. It is not possible to exclude the possibility of these fluctuations deriving from lamp instability rather than intrinsic instability in the devices. Nevertheless, the overall small magnitude of the observed drift suggests that very sensitive detection of fading changes should be possible with all of these devices.

2. Fading test performance

The preceding evaluations suggest that the accuracy and precision of the color difference measurements are sufficient so that all of the devices can be used as fading tester detectors for tests of relatively fugitive colors (less lightfast than about Blue Wool #3). To verify this would require a comprehensive survey of many materials. Instead, we performed fading tests of only a few very fugitive colored materials that had been extensively examined in prior studies: Blue Wool #1, and five samples of very unstable gouaches painted onto paper. For each of these samples, fading tests were repeated on five different areas consecutively. Small variations in the results of these repeated tests simply reflect the non-uniformity of the samples, and reasonably precise groupings of fading rate curves only testifies to the ability of the device to perform this function in a reasonably routine manner.

The results of these multiple-trial fading tests are shown in Figures 9a-f. Without exception, all of the devices provided good results for the fading tests of the Blue Wool #1 and the gouache samples, with reasonably good precision and good reproducibility regardless of the device used.

3. Low CCT illumination performance

Since many art display environments are illuminated with incandescent lamps, the color stability of materials when exposed to these sources having low correlated color temperatures (CCT) is a reasonable behavior to measure in a fading test. As reported in earlier work (Whitmore et al. 2000), it is easy to create these illumination conditions in the fading tester using a colored glass filter in the lamp to absorb the blue wavelengths of the source. As we also learned in that study, however, reflectance spectra are more difficult to obtain under those conditions, for they are at best subject to noise at the blue wavelengths where there is little light to detect, and at worst subject to spurious artifacts from the stray light or higher-order diffracted light in the detector, if any. With the first prototype device, the latter problem made it impossible to make good reflectance measurements using the filtered source. To do the fading test, it was necessary to expose the sample to the low color temperature light, then remove the filter to measure a reflectance spectrum with the high color temperature (unfiltered) source, and to repeat the procedure during the course of the test.

In this evaluation, the devices were used to see if reasonable reflectance spectra could be obtained with a low color temperature source, and whether reasonable fading tests could be performed under these conditions.

a. Reflectance spectra

In order to get a sense of the capability of the devices when used with the low color temperature source, a reflectance spectrum of a standard white tile was made with the low-temperature source after calibrating the reflectance measurement using the high-temperature source. In essence, this produces a reflectance spectrum of the white tile under low-temperature illumination ratioed to the spectrum measured under high-temperature light. The results for the five devices are shown in Figure 10, with each reflectance spectrum compared to the irradiance spectrum of the filtered source (in this case, represented by the transmission spectrum of the glass filter used to alter the source, measured on the standard spectrophotometer). With one exception, the devices each measured a reasonably good spectrum of the low-temperature source, albeit with an unusual offset (and spectral artifacts described above) for the spectrum measured by the StellarNet device. The exception to this was the Data Optics device, which not only showed deviations of the spectrum at the high wavelengths, but showed significant reflectance (about 3%) at the low wavelengths, where the nominal reflectance was nearly zero. This result is very similar to that observed with the first prototype, which was at that time attributed to stray light or higher-order diffracted light reaching the detector. This same explanation is likely here as well: the Data Optics device is the only one of the five that has no order-sorting filter on the detector array to protect against the higher order diffracted red light from overwhelming the very small signal from the first-order diffracted blue light.

This possible shortcoming of the Data Optics device was made obvious in measurements of the reflectance spectrum of Blue Wool #1 under the low-temperature source (shown in Figure 11). For the other four devices, the blue end of the spectrum is very noisy, due to the noise in the white tile reference spectrum, which is divided into the Blue Wool spectrum in order to get relative reflectances. So with the exception of the spectrum measured with the Data Optics device, the Blue Wool spectra measured with the other devices have significant, but relatively constant (because they derive mostly from the constant reference spectrum), noise levels superimposed on the spectra at the blue wavelengths. Because this noise originates from a noisy reference spectrum, further signal averaging by integrating or averaging the sample spectrum does little to improve the noise levels.

The seemingly slight problem of the stray light in the Data Optics detector becomes a very serious problem in the reflectance spectrum of a sample. Where the other devices had noise at the blue wavelengths, which for the Control Development device was only a few percent reflectance, the Data Optics device produced an essentially noise-free but spurious artifact in the spectrum at those wavelengths. From our experience with a similar problem with the first fading tester prototype, there is little that can be done to remedy this because the problem derives not from noise, but from stray light.

b. Fading test performance

Since these devices seem to measure such noisy or inaccurate reflectance spectra at the blue wavelengths, it may seem foolish to evaluate their performance as fading tester detectors using a low correlated color temperature source. However, as noted above, the problems at the blue end of the spectrum are relatively constant, so they may not interfere with quantification of relatively large spectral changes occurring at other wavelengths. This was proven to be the case for the Blue Wool #1 fading tests, shown in Figure 12. While less smoothly varying, and producing fading at only about half the rate as with the higher-temperature source, the fading of the Blue Wool #1 is well defined by all the devices except the StellarNet, whose very erratic color differences suggest more significant noise problems in the reflectance spectra.

4. Software evaluation

More than any other feature, the software that is provided with the spectrometers will determine the capability and ease-of-use of the devices. Yet the software package is also the most short-lived aspect of these devices, and new revisions of the software are likely to be available frequently. As a result, this section of the report will deal mostly with the software features that have been found useful, and how the software provided at the time of this writing compare in terms of those features. Later revisions, or user-written controlling software, should be judged on the basis of the additions of these useful features.

The most basic function of the software is to control the acquisition of spectral data from the device. All the packages obviously performed that task. However, there were clear instances where versatility and flexibility in the spectral acquisition was required. For example, measurements made with lower light intensities, whether because of very highly absorbing samples or low correlated color temperature source illumination, could be improved by increasing the integration time (allowing the detector to collect more light signal before being sampled by the electronics) or the number of spectra to be averaged. Two of the software packages lacked one or the other of these capabilities: the American Holographic did not allow variable sample averaging, and the Data Optics Specbos Color software had a fixed integration time (the

Specbos spectral software allowed selection of integration time, but it provided no colorimetric data). In fact, when used as the detector in the fading tester, the Data Optics device could not deal with the high light intensities, and since the integration time could not be adjusted, the collection lens had to be defocused to provide a light signal low enough to be in the working range of the device.

Another convenient feature when the device is used as a fading tester detector is the ability to acquire and store reflectance spectra automatically and repetitively. This feature not only allows convenience when performing fading tests, but it also is needed when adjusting the position of the tester optics above the sample (the tester is optimally positioned above the sample when the reflectance signal is maximized, and this is most convenient if the software repetitively updates the reflectance spectrum while position adjustments are made). All but the Data Optics package allowed automatic repetitive data collection. Although the software allowed this function, the American Holographics device displayed some erratic behavior when spectra were acquired in repetitive mode, showing erratic reflectance values between 375 and 395 nm. While most of the packages allowed this automatic data collection, only the Control Development software allowed automatic repetitive saving of data to the hard drive.

The use of the device as a fading tester requires translation of the reflectance spectra into color attributes, and ultimately calculation of color differences. Ideally, these data would also be calculated automatically and repetitively, so that the progress of fading could be monitored in "real time" during the test, so as to rapidly assess the result and to avoid accidental over-bleaching of the test areas. One of the devices, American Holographic, had no colorimetric calculation capabilities, and results had to be calculated off-line in Excel spreadsheets. The Data Optics Specbos Color package could display reflectance, colorimetric, and A/D counts data, but it only allowed saving of reflectance and colorimetric data (the Specbos spectral package was used to save A/D counts data for the UVA lamp measurement). StellarNet had color calculation software available as a separate application within the SpectraWiz software, but SpectraWiz itself could not be accessed while the color application was running. The Ocean Optics package calculated colorimetric quantities, but color differences had to be calculated by hand. The only software package that came with built-in automatic color and color difference calculations was that of Control Development.

Finally, the Ocean Optics package was alone in providing another feature that could be useful. That software provided measured light intensities in lumens, and with proper calibration this might make it possible to use the spectrometer to measure the light output of the source, thus dispensing with the need to make separate irradiance measurements with a radiometer when optimizing the lamp.

The details of the function and noteworthy performance attributes of the software packages is described in Appendix 2.

SUMMARY AND CONCLUSIONS

In this project, five commercially available fiberoptic-based photodiode array spectrometers were examined and compared for their usability as the detector in a fading tester. The essential performance criteria for this use were described and the devices were tested for their ability to measure accurate, precise, and stable reflectance spectra, which would allow sensitive and reliable measurements of color changes due to fading. A summary of those criteria and the device performance evaluations is shown in Table 5. While there were slight differences in capability, each of the five devices were found to be adequate for use as detectors in the fading tester. Two of the devices, Ocean Optics and StellarNet, had some intrinsic limitations that added artifacts to measured spectra, and this might make them somewhat less desirable options should one choose to use them for other functions besides fading test detectors. For use in fading tests that use illumination sources of low correlated color temperature, however— as would be done to assess color stability in environments lit with incandescent lamps— the Data Optics and StellarNet devices were clearly poor performers, and either recorded inaccurate or very unstable spectra. Finally, the software packages that were provided with the devices were evaluated and compared for their usability in fading tester applications. In terms of its overall performance and the functionality of the controlling software, the Control Development spectrometer seems to offer overall superior performance for use as the detector in a fading tester.

APPENDIX 1. Experimental Procedures

Fading tester optimization

For every test in which the fading tester as a whole was used, the lamp was allowed to warm up for 1 hour prior to use. The lamp was positioned to maximize the irradiance of the light emerging from the illumination fiber, as measured by a radiometer. The power of the lamp was adjusted to achieve an irradiance of 0.700 lumens. The position of the test head and the fibers within the test head were adjusted to maximize the raw A/D counts signal of a white $BaSO_4$ reference tile, measured in reflectance. Light and dark references were taken with and without the white tile in place, respectively.

UVA lamp measurement

An integrating sphere (2-inch diameter, manufactured by Ancal, Inc.) was placed on the center of a shelf below a bank of ten UVA lamps (Q-Panel No. UVA-351). A dark reference was taken with a black plastic cap over the fiber port of each spectrometer. The integrating sphere was then connected with an optical fiber (400-µm core) to the fiber port of each spectrometer, and the spectrometer's integration time was set so that the raw A/D counts signal of the lamps was maximized without saturating the detector.

Reference tile measurement

After optimizing the fading tester, the reflectances of five standard tiles (beige, blue brown, green, and pink; from Kollmorgen, Inc.) were measured. These measurements were compared to reflectance measurements of the same tiles using the Color Eye.

Munsell chip measurement

After optimizing the fading tester, the reflectance and colorimetric data of 11 pairs (one pair of each hue) of Munsell chips (from Kollmorgen, Inc.'s *Munsell Book of Color*, 1976) were measured, and color differences (ΔE values) within each pair were measured. These measurements were compared to the corresponding color differences within each pair as measured by the Color Eye.

Stability testing

After optimizing the fading tester, the reflectance and colorimetric data of the green standard tile were measured, for both 30 minutes (saving data every minute) and for 8 hours (saving data every 30 minutes).

Measurement of white reference tile with low-correlated-color-temperature filter

After optimizing the fading tester, the reflectance of the white reference tile was measured with the low-CCT filter (Schott FG-13, 2.0 mm thick) between the lamp and the illumination fiber. The data from each spectrometer was compared to the Color Eye measurement of the low-CCT filter in transmission.

Blue Wool 1 fading tests (with and without low-correlated-color-temperature filter)
After optimizing the fading tester, a Blue Wool 1 cloth was illuminated by the fading tester. The test head was moved so that the illuminated spot on the cloth coincided with the area viewed by the collection fiber. The cloth was moved until it was clear that the light was focused on the top of one of the cloth's fibers (i.e., the reflectance was maximized). The reflectance and colorimetric measurements of the cloth at the start of the test were set as references, and the test data were saved every minute for 30 minutes. For the low-CCT fading tests, the raw counts curve of the white reference tile (with the low-CCT filter in place) was maximized by increasing the integration time (or, in the case of the Data Optics spectrometer, the focus of the collection fiber was tightened). The reflectance of the low-CCT-illuminated white tile was set as 100% reflectance. The remainder of the procedure for these tests is the same as for the unfiltered Blue Wool 1 tests above.

Gouache fading tests
After optimizing the fading tester, a sample of Winsor & Newton designer's gouache (painted onto watercolor paper) was illuminated by the fading tester. Bengal Rose, Geranium, Magenta, Rose Malmaison, and Rose Tyrien gouaches were used. Because of the extremely poor lightfastness of these gouaches, the fluorescent room lights were turned off during these tests to prevent fading of the samples during multiple prolonged tests. The test head was moved so that the illuminated spot on the sample coincided with the area viewed by the collection fiber. The reflectance of the gouache at the start of the test was set as the reference, and the colorimetric and reflectance data were saved every minute for 20 minutes.

Software settings

American Holographic – software: EasySpec 2000
Integration time: 20 ms (for UVA measurement: 2500 ms; for low-CCT Blue Wool 1 fading: 280 ms); Raw counts peak: approx. 28,000 counts (max at 65,535 counts).

Control Development – software: CDI SPEC
Integration time: 0.016002 s (for UVA measurement: 0.65002 s; for low-CCT Blue Wool 1 fading: 0.035002 s); Sample avg.: 10; Raw counts peak: approx. 52,000 counts (max at 65,500 counts). Reference illuminant: C; Observer: CIE 1931 2 degree.

Data Optics – software: Specbos (for UVA measurement only)
Integration time: 120 ms; Sample avg.: 10.

Data Optics – software: Specbos Color (for all other measurements)
Sample avg.: 10; Raw counts peak: approx. 14,000 counts (max at approx. 15,500 counts); Reference illuminant: C; Observer: 2 degree.

Ocean Optics – software: OOIIrrad
Integration time: 31 ms (for UVA measurement: 1000 ms; for low-CCT Blue Wool 1 fading: 120 ms); Sample avg.: 10; Smoothing size: 0; Raw counts peak: approx. 2400 counts (max at approx. 4000 counts); Reference illuminant: C; Observer: 2 degree CIE (1931).

StellarNet – software: SpectraWiz
Integration time: 7 ms (for UVA measurement: 300 ms; for low-CCT Blue Wool 1 fading: 68 ms); Sample avg.: 10; Smooth: 0; Temperature compensation: on; resolution control: 2; Raw counts peak: approx. 2000 counts (max at approx. 4000 counts); Reference illuminant: C.

Appendix 2. Software evaluation

American Holographic – software: EasySpec 2000
Repetitive data acquisition possible, but data cannot be saved automatically. No colorimetry software – Excel spreadsheet constructed to perform color calculations. Occasionally, when acquiring data in "repetitive" mode, curve "hops up" between 375 and 395 nm (occasionally as high as 405 nm). This does not occur when data is acquired manually.

Control Development – software: CDI SPEC
Repetitive data acquisition and automatic saving possible. Colorimetric data acquired and calculated. ΔE can be displayed in real time.

Data Optics – software: Specbos Color
One program (Specbos) for spectral measurements, another (Specbos Color) for spectral and colorimetric measurements. However, raw counts data cannot be saved in Specbos Color. Detector was saturated after optimizing lamp and acquiring white tile reflectance data, so collection fiber was defocused (cannot change integration time). No repetitive data acquisition (this makes fading tester alignment extremely inconvenient, since data must be manually acquired) or automatic data saving capability (data saving is awkward – must "start link" and then save each sample; data can be saved as ASCII or Excel 97 files, but only Excel mode saves ΔE values). In addition to spectra, colorimetric data can be displayed as x-y, a*-b*, or u*-v* plots.

Ocean Optics – software: OOIIrrad
Repetitive data acquisition possible, but no automatic saving capability. Colorimetric data acquired and calculated, but ΔE values are absent (in both display and data files). Chromaticity coordinate plot can be displayed. Data can also be displayed in lumens, which could eliminate the need to optimize lamp using a radiometer.

StellarNet – software: SpectraWiz
Repetitive data acquisition possible, but no automatic saving capability. Colorimetric data acquired and calculated in a separate application within SpectraWiz, but reflectance data cannot be accessed while this application is running. Color application also has an a*-b* plot and an L* bar, and displays ΔE values in real time. Some software glitches were apparent: entering non-integer integration time values causes the program to crash; occasionally, light and dark references only "take" after two tries; after canceling an "Open" or "Save as…" operation, the previously displayed spectrum disappears and the software stops updating the spectrum.

REFERENCES

Whitmore, P., C. Bailie, and S. A. Connors. 2000. Microfading tests to predict the result of exhibition: Progress and prospects. In *Tradition and Innovation: Advances in Conservation*, ed. A. Roy and P. Smith. London: International Institute for Conservation. 200-5.

Whitmore, P., X. Pan, and C. Bailie. 1999. Predicting the fading of objects: Identification of fugitive colorants through direct nondestructive lightfastness measurements. *J. of the American Institute for Conservation* **38**: 395-409.

Table 1. Manufacturers' Performance Specifications for Five Spectrometers

	American Holographic (Model AH6130)	**Control Development (Model PDA)**	**Data Optics (Model Specbos1000)**	**Ocean Optics (Model S1024DW)**	**StellarNet (Model EPP2000C)**
Spectral range	190-1100nm (375-750nm used)	200-1100nm (380-900nm used)	240-760nm (380-760nm used)	200-1100nm (350-850nm used)	200-850nm used (others w/ other models)
Detector	512-element PDA	512-element PDA	128-element PDA	1024-element PDA	2048-element PDA
Grating type	Concave holographic	Ruled	Holographic	Holographic	Concave holographic
Order-sorting filter	Yes	Yes	No	Yes	Yes
Spectral resolution	1-4 nm	unspecified	6 nm w/50μm fiber	0.3 - 10 nm	< 0.75 nm
Wavelength accuracy	unspecified	< 0.25 nm	1 nm	1 nm	< 0.25 nm
Stray light	0.001% T	0.1% (higher at lower wavelengths)	$< 10^{-4}$	< 0.05% @ 600nm, < 0.10% @ 435nm and 250nm	0.02% @ 435nm, 0.2% @ 220nm
Noise level	unspecified	0.4 counts RMS, 1024 point sample, 6 msec accumulation per point	Signal:noise = 5000:1	Dark noise = 1-2 RMS; Signal:noise = 2500:1	Signal:noise = 2000:1
A/D converter resolution	16-bit	16-bit	14-bit	12-bit	12-bit
Dynamic range	8 decades	> 10,000:1	5000:1	unspecified	7 decades
Input slit	25 μm slit used (others available)	25, 50, 100μm slit (100 μm used)	50, 100μm core internal fiber (100μm used), no slit	5, 10, 25, 50, 100, 200μm slit (100 μm used)	25μm slit
Integration time	20 msec - 4 min	1.6 msec - 2.8 min	10 msec - 5 sec for Specbos; fixed but unspecified for Specbos Color	31 msec - 65 sec	4 msec - 60 sec
Computer requirements	WIN 95/98/NT, 486 or better, 16MB RAM, 2.5MB disk space, connects via serial port	WIN 95/98/NT, 386 or better, 2.5MB disk space, connects via PCMCIA card	WIN 95/98/NT, 486 or better, 16MB RAM, 2.5MB disk space, EXCEL 97, connects via serial port	WIN 95/98/NT, 486 or better, 16MB RAM, 4MB disk space, connects via serial port or PCMCIA card	WIN 95/98/NT, <1.5MB disk space, connects via PCMCIA card
Colorimetry software	none	Yes	Yes (spectral and colorimetry software are two separate packages)	Yes, but not included	Yes (spectral and colorimetry measurements cannot be viewed simultaneously)
Price	$3,750	$2,995	$2,195 (includes spectrometer, 100μm fiber)	$3,647 (includes spectrometer, slit, A/D board, colorimetry software)	$2,720 (includes spectrometer, slit, PDA upgrade)

Table 2. Calculated tristimulus values for the spectra measured with the fading tester and standard spectrometer shown in Figure 2.

	Color Eye	**American Holographic**	**Control Development**	**Data Optics**	**Ocean Optics**	**StellarNet**
Beige tile						
X	44.16	46.15	47.94	46.82	43.70	44.46
Y	43.40	46.01	47.79	46.31	43.60	44.45
Z	37.85	41.84	42.24	40.68	39.45	38.43
Blue tile						
X	43.71	48.98	53.31	47.89	45.73	48.98
Y	47.39	52.66	57.42	51.79	49.20	53.42
Z	72.88	78.18	84.53	78.74	73.46	80.30
Brown tile						
X	15.46	17.90	18.95	17.35	16.79	15.75
Y	14.54	16.90	17.90	16.35	15.89	14.92
Z	10.05	11.53	11.94	11.37	10.83	9.38
Green tile						
X	32.73	28.51	30.24	33.01	27.50	28.08
Y	39.13	32.39	34.37	38.62	31.29	32.70
Z	42.83	36.90	38.68	43.25	36.04	36.70
Pink tile						
X	48.80	57.28	62.12	55.13	54.44	57.96
Y	46.03	54.53	59.16	52.13	52.17	55.54
Z	43.42	52.00	56.03	49.12	49.58	50.56

Table 3. Color differences ΔE (CIE 1976 L*a*b*) between fading tester spectral measurements and standard spectral measurements for results shown in Figure 2.

	American Holographic	Control Development	Data Optics	Ocean Optics	StellarNet
Beige tile	2.957	3.441	2.035	2.528	2.261
Blue tile	3.693	6.059	2.732	2.104	3.883
Brown tile	3.390	4.791	2.472	2.085	2.955
Green tile	8.726	7.583	2.870	9.415	6.502
Pink tile	5.247	7.829	3.829	4.185	6.459

Table 4. Summary of software capabilities for five devices

	American Holographic (EasySpec 2000)	Control Development (CDI SPEC)	Data Optics (Specbos Color)	Ocean Optics (OOIIrrad)	StellarNet (SpectraWiz)
Adjustable integration time	Yes	Yes	No	Yes	Yes
Adjustable sample average	No	Yes	Yes	Yes	Yes
Repetitive data acquisition	Yes, but erratic behavior	Yes	No	Yes	Yes
Automatic data saving	No	Yes	No	No	No
Colorimetric calculations	No	Yes	Yes, but color package cannot save raw counts (need separate spectral package)	Yes, but no ΔE calculations	Yes, but in separate "sub-application" that cannot be used while accessing spectral data
"Real-time" ΔE display	No	Yes	No	No	Yes
Data display in lumens	No	No	No	Yes	No

Table 5. Summary of performance evaluation for five spectrometers

	American Holographic	Control Development	Data Optics	Ocean Optics	StellarNet
Noise	+	+	+	+	+
Stray light	+	+	+	+	+
Wavelength resolution	+	+	+	+	+
Accuracy of spectra	+	+	+	−	−
Accuracy of color differences	+	+	+	+	+
Stability	+	+	+	+	+
Fading tester performance	+	+	+	+	+
Low CCT spectra	+	+	−	+	+
Low CCT fading tester performance	+	+	+	+	−
Software capability	−	+	−	−	−

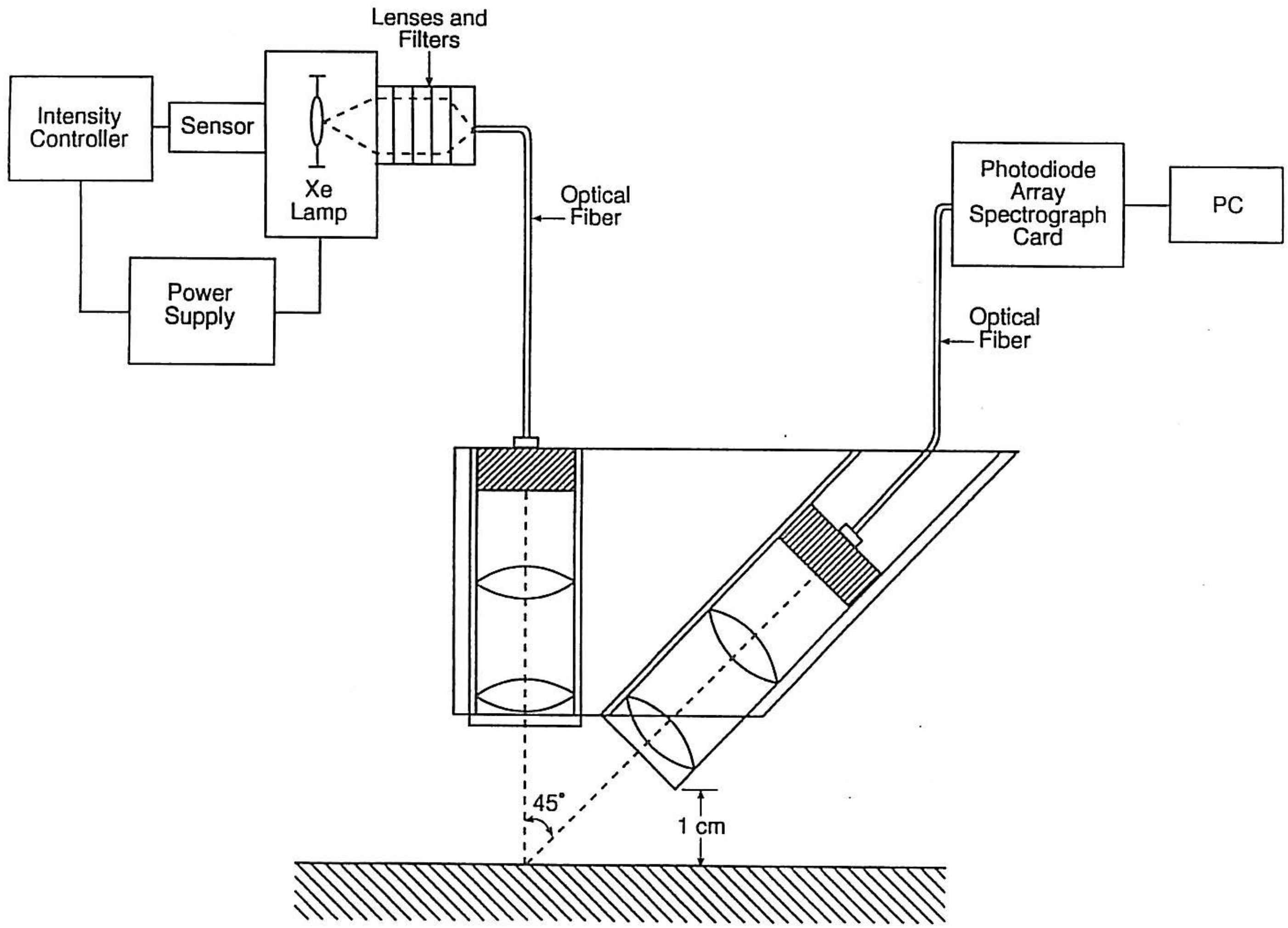

Figure 1. Schematic of fading tester prototype. Figure reproduced from Whitmore, Pan, and Bailie 1999.

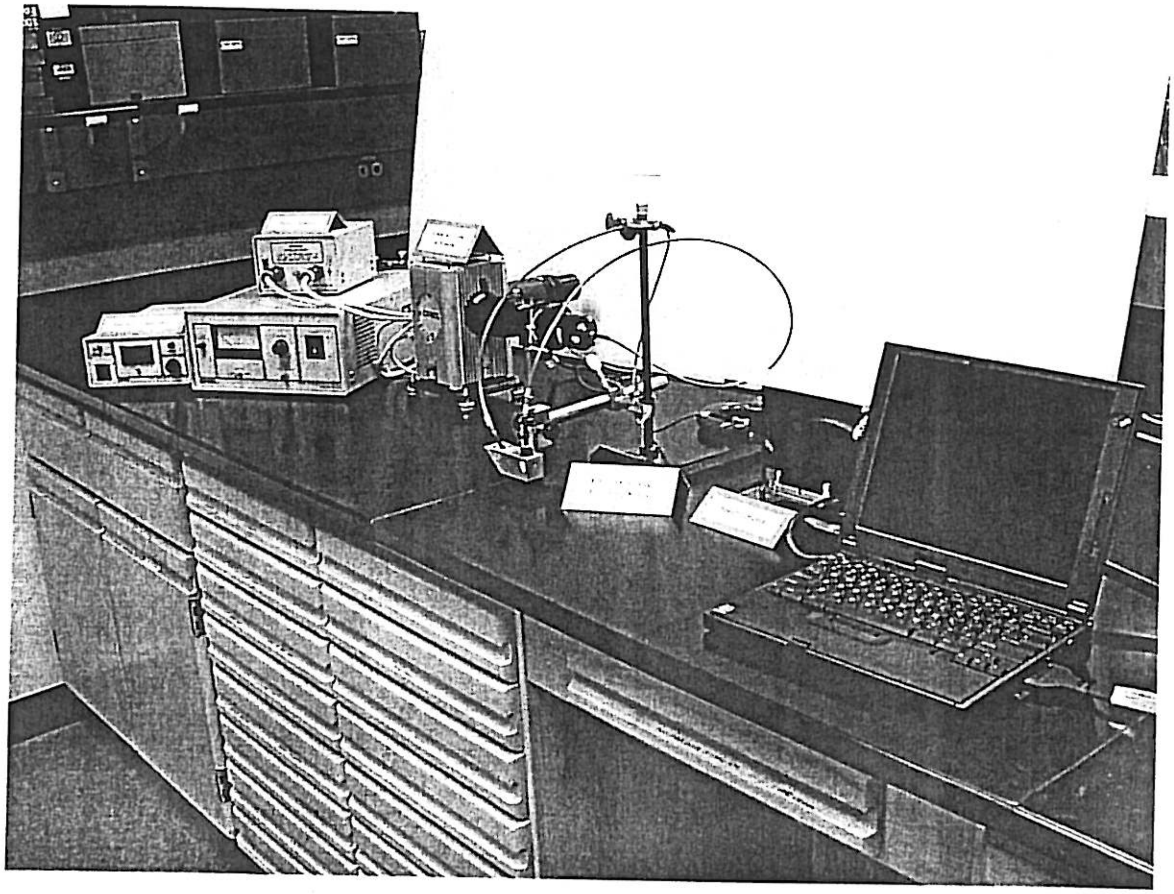

Figure 2. Photo of fading tester prototype.

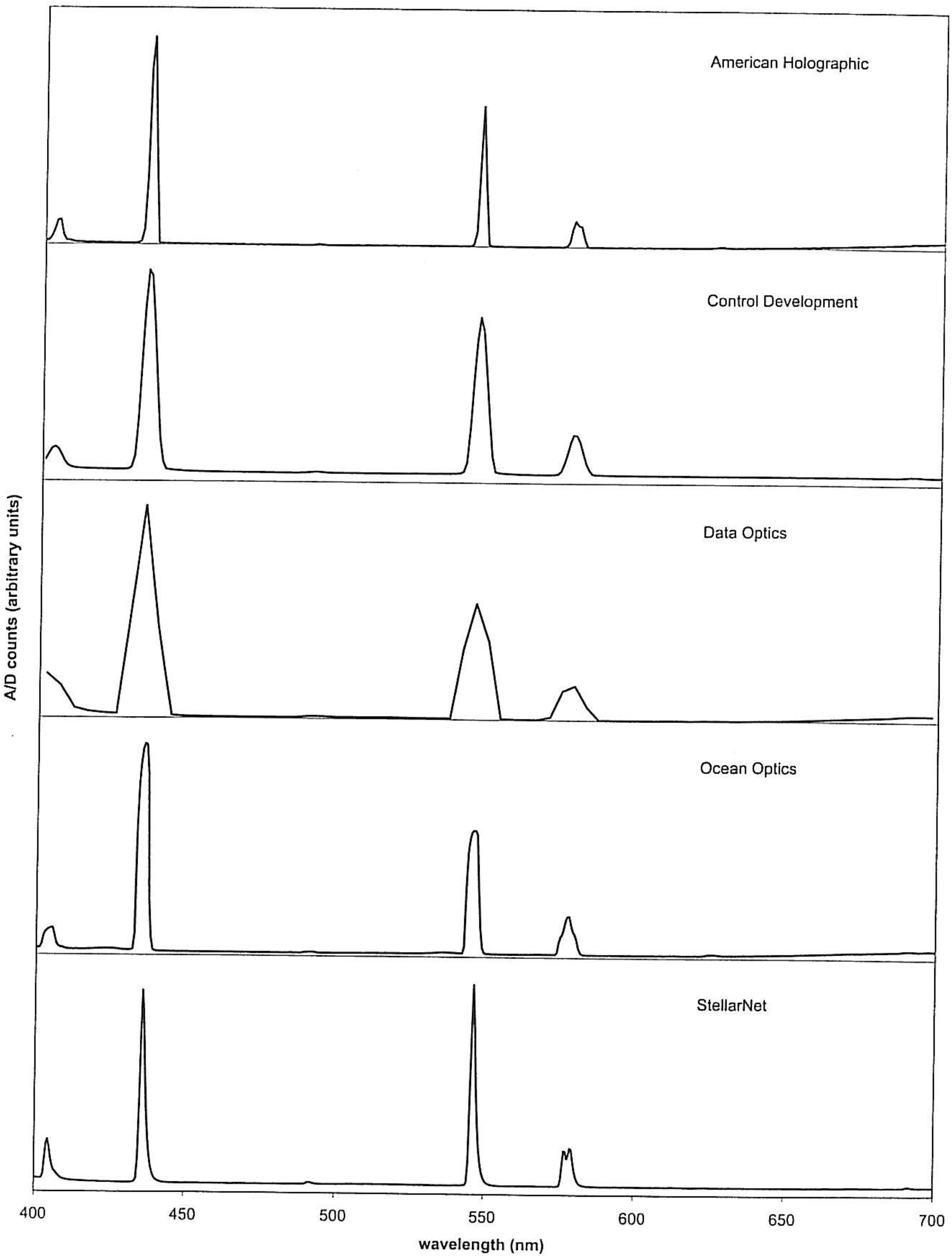

Figure 3. Spectral output of UVA fluorescent lamp (Q-Panel UVA-351) measured by the five spectrometers.

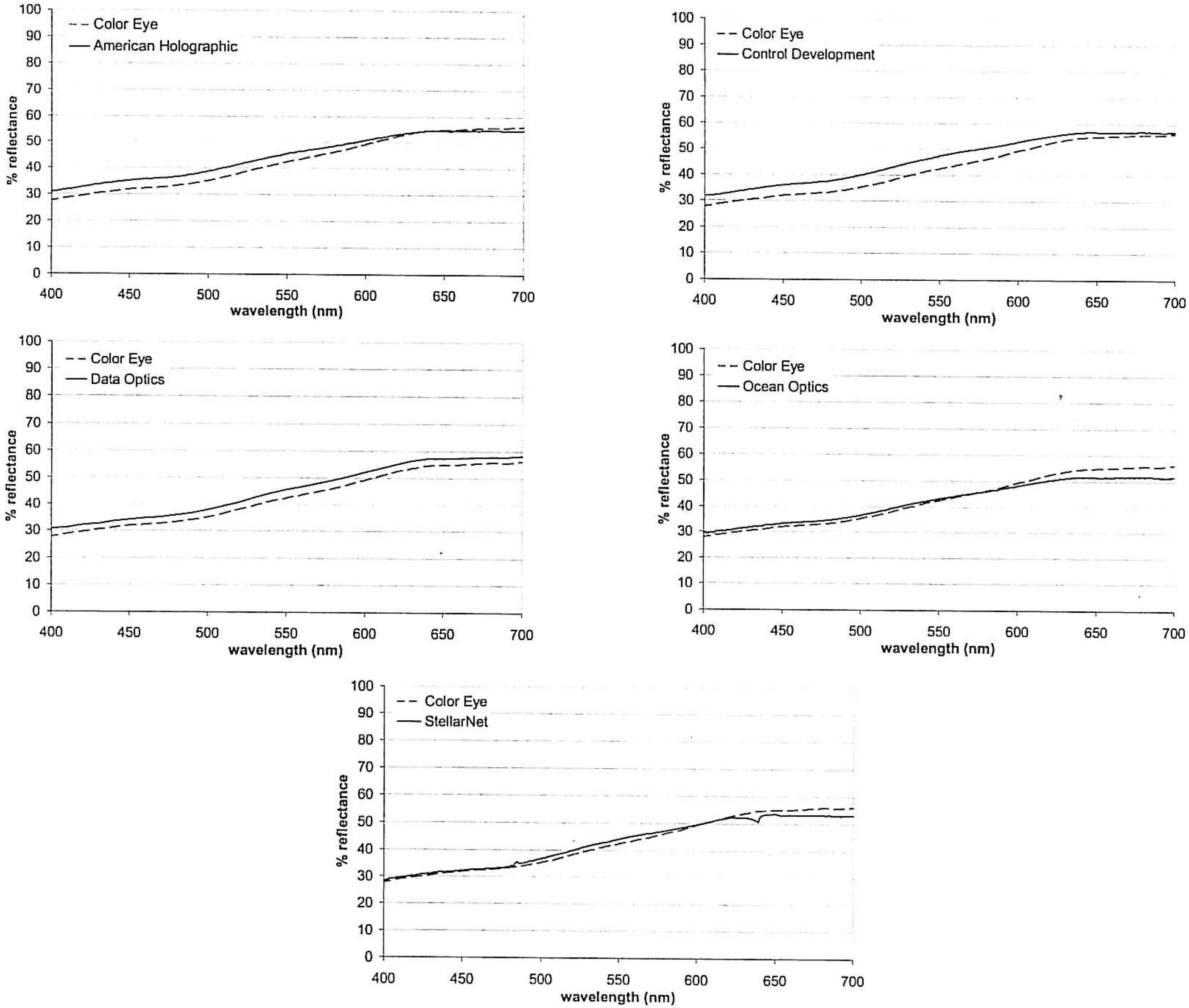

Figure 4a. Spectra of beige standard tile measured by each spectrometer in fading tester geometry (0° / 45°) vs. standard spectrometer (diffuse / 0°).

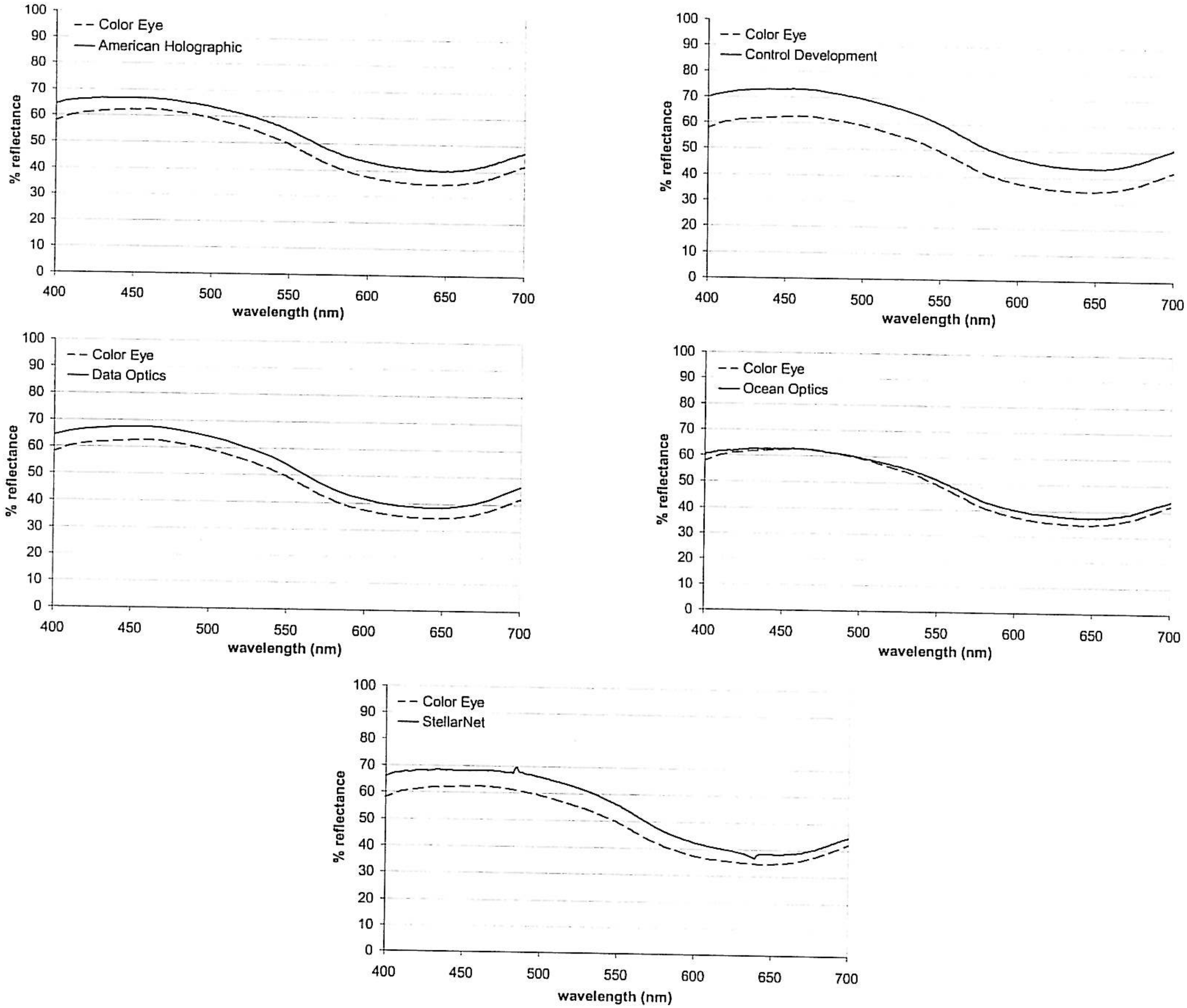

Figure 4b. Spectra of blue standard tile measured by each spectrometer in fading tester geometry (0° / 45°) vs. standard spectrometer (diffuse / 0°).

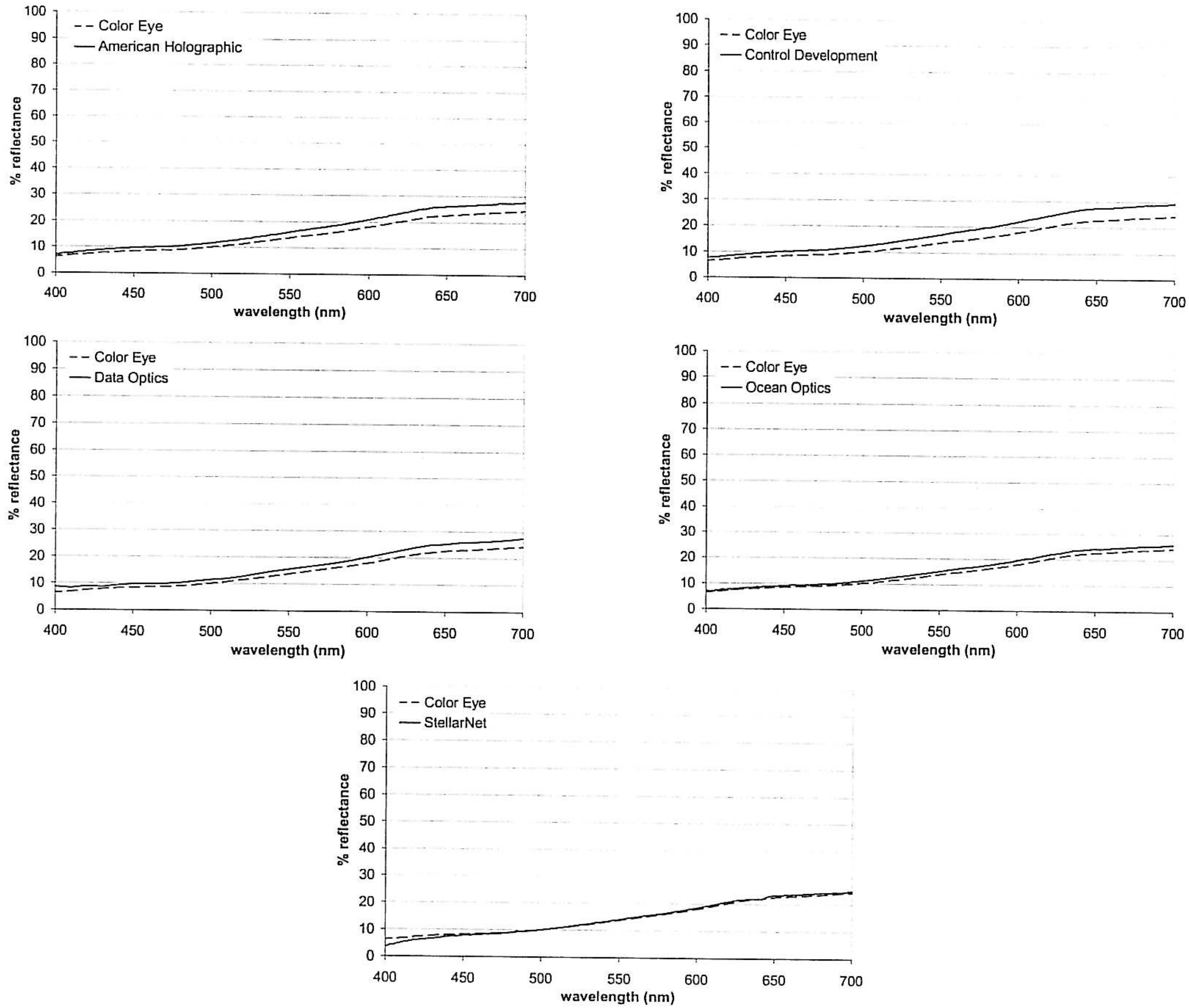

Figure 4c. Spectra of brown standard tile measured by each spectrometer in fading tester geometry (0° / 45°) vs. standard spectrometer (diffuse / 0°).

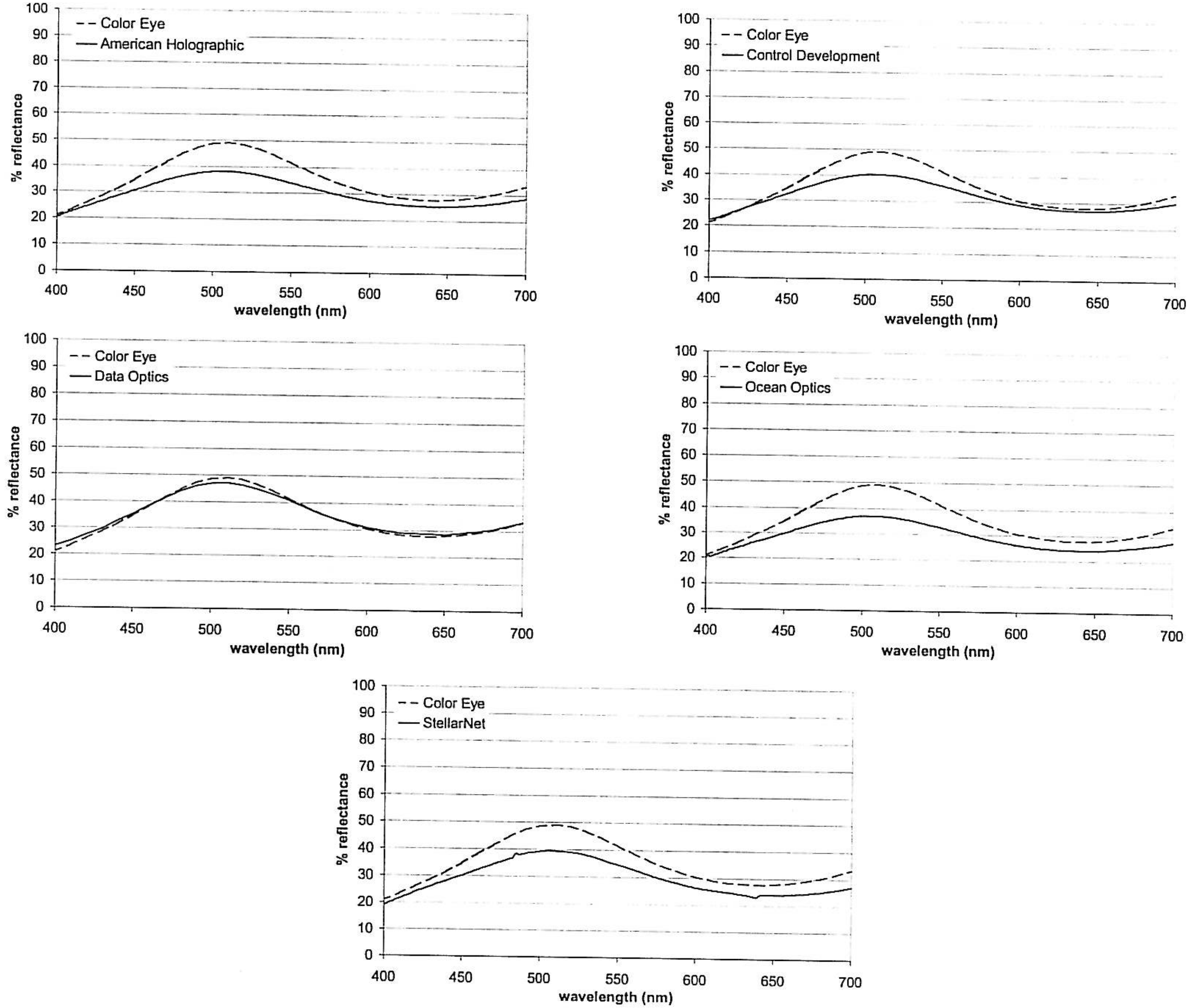

Figure 4d. Spectra of green standard tile measured by each spectrometer in fading tester geometry (0° / 45°) vs. standard spectrometer (diffuse / 0°).

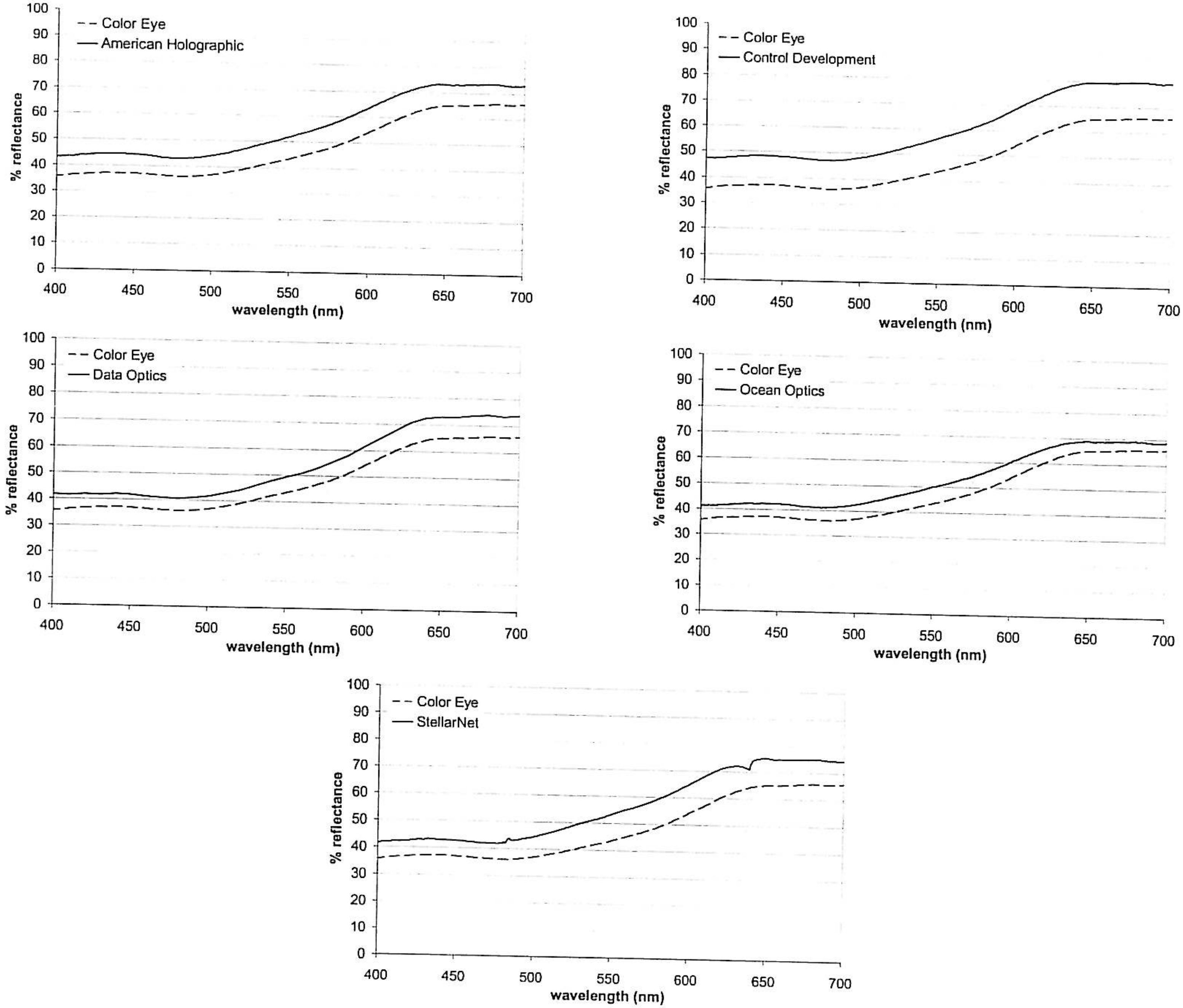

Figure 4e. Spectra of pink standard tile measured by each spectrometer in fading tester geometry (0° / 45°) vs. standard spectrometer (diffuse / 0°).

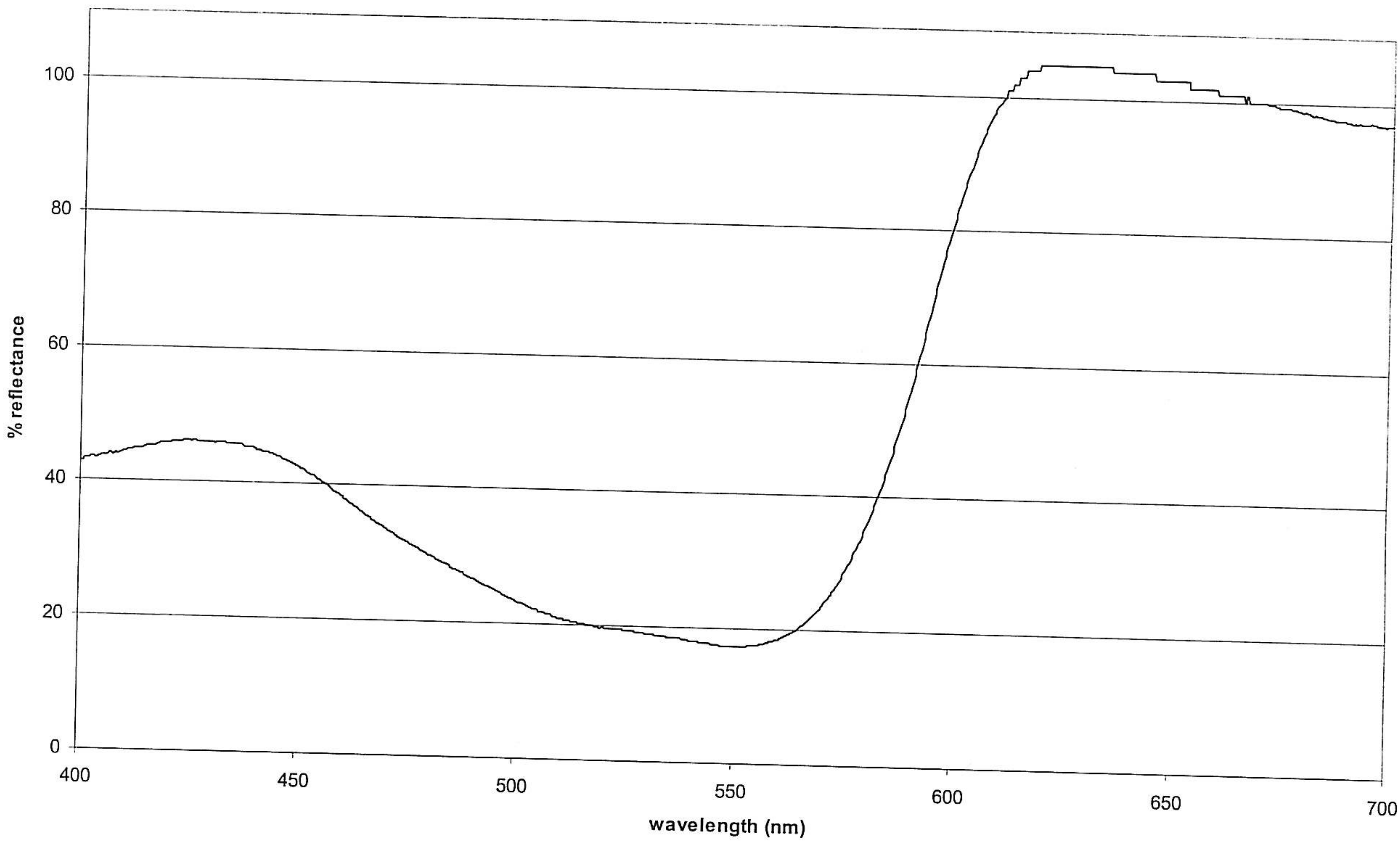

Figure 5. Reflectance spectrum of Bengal Rose gouache taken with the Ocean Optics spectrometer in the fading tester. The abrupt changes in the reflectance data between 600 nm and 650 nm are due to low precision of the acquired data.

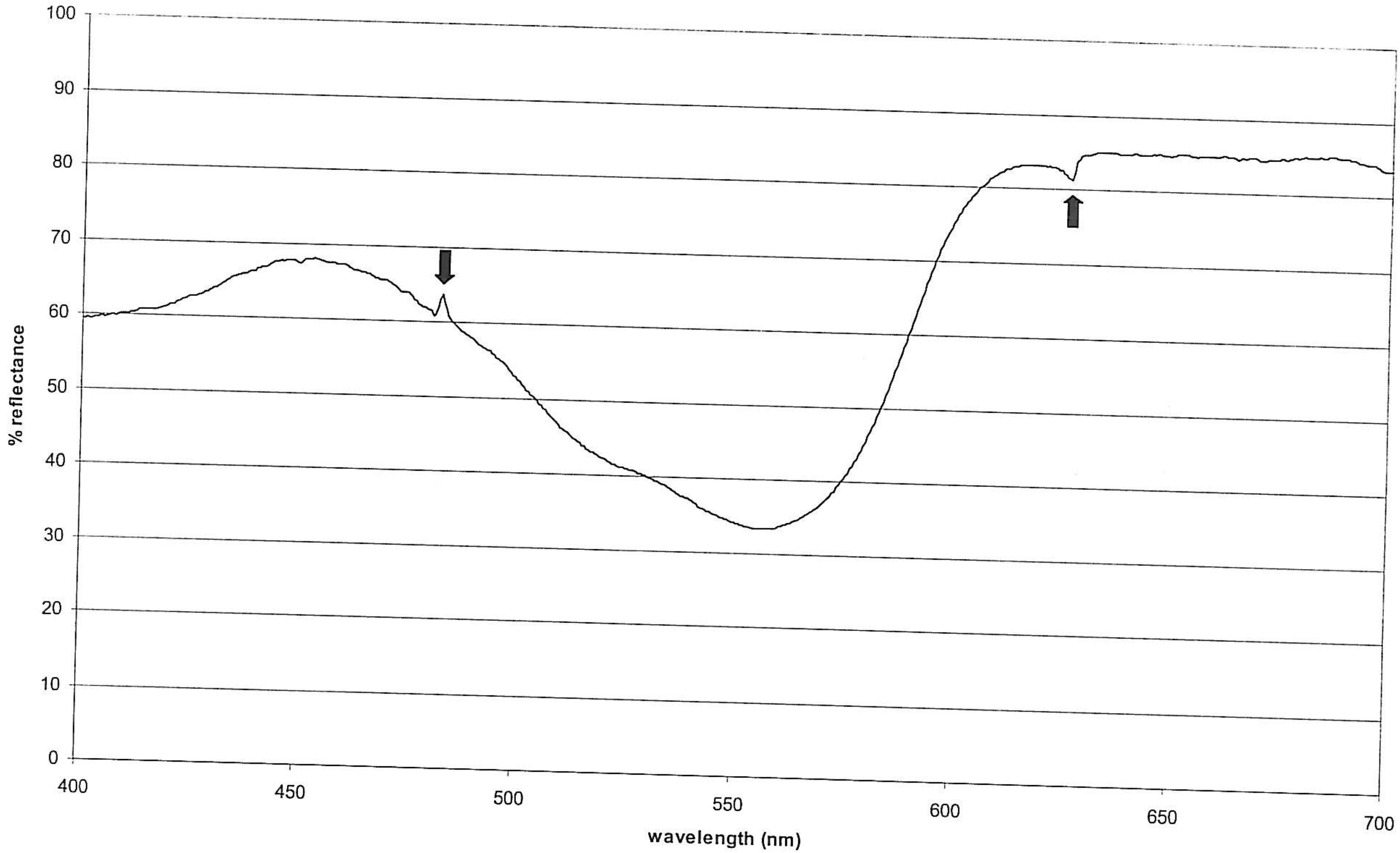

Figure 6. Reflectance spectrum of Rose Tyrien gouache taken with the StellarNet spectrometer in the fading tester. The irregularities of the spectrum at 490 nm and 620 nm are due to discontinuities in the recorded spectrum that occur with this device.

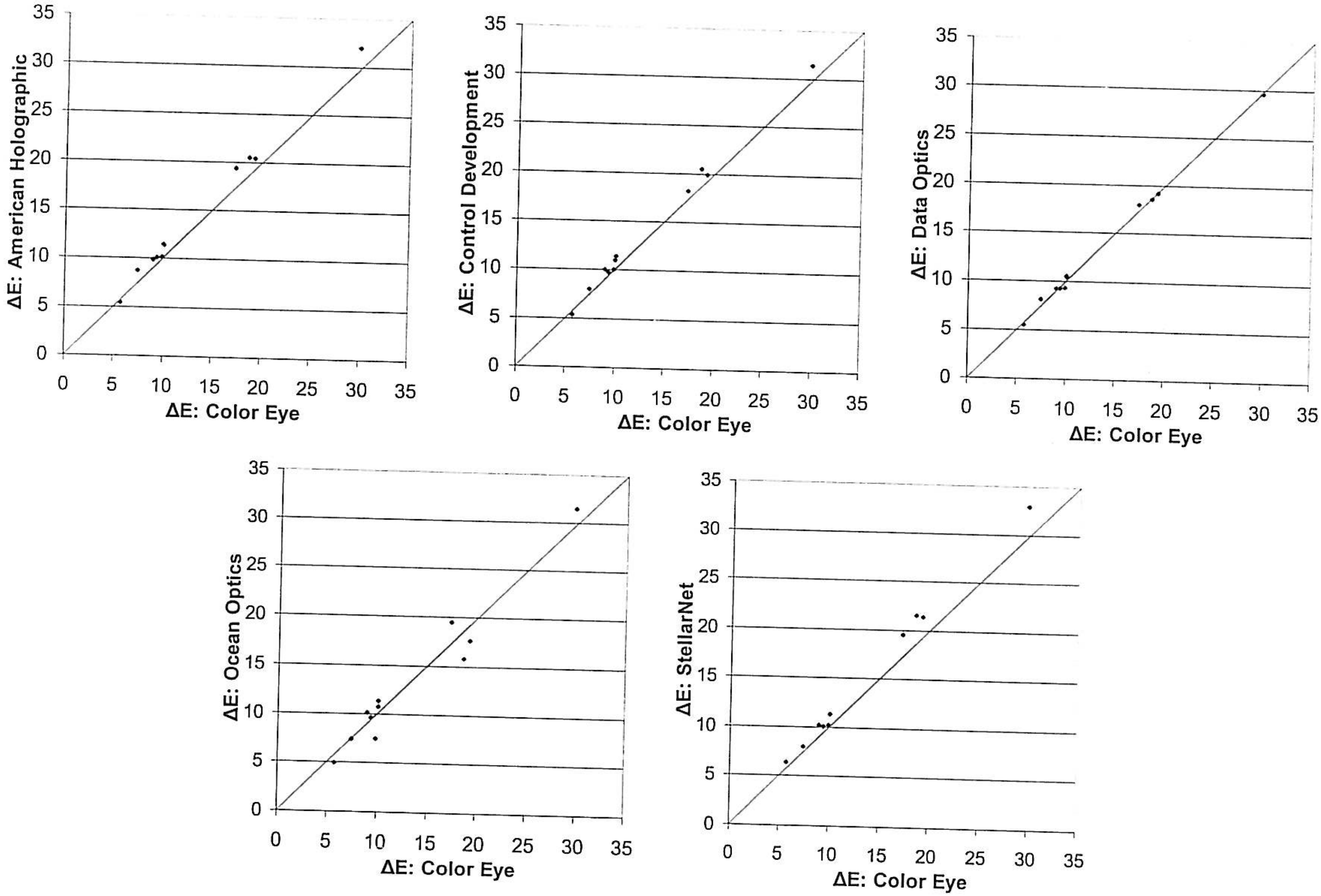

Figure 7. Comparison of calculated color differences (CIE 1976 L*a*b* equation) between pairs of Munsell color chips measured in the fading tester (using each of the five spectrometers) and the standard spectrometer.

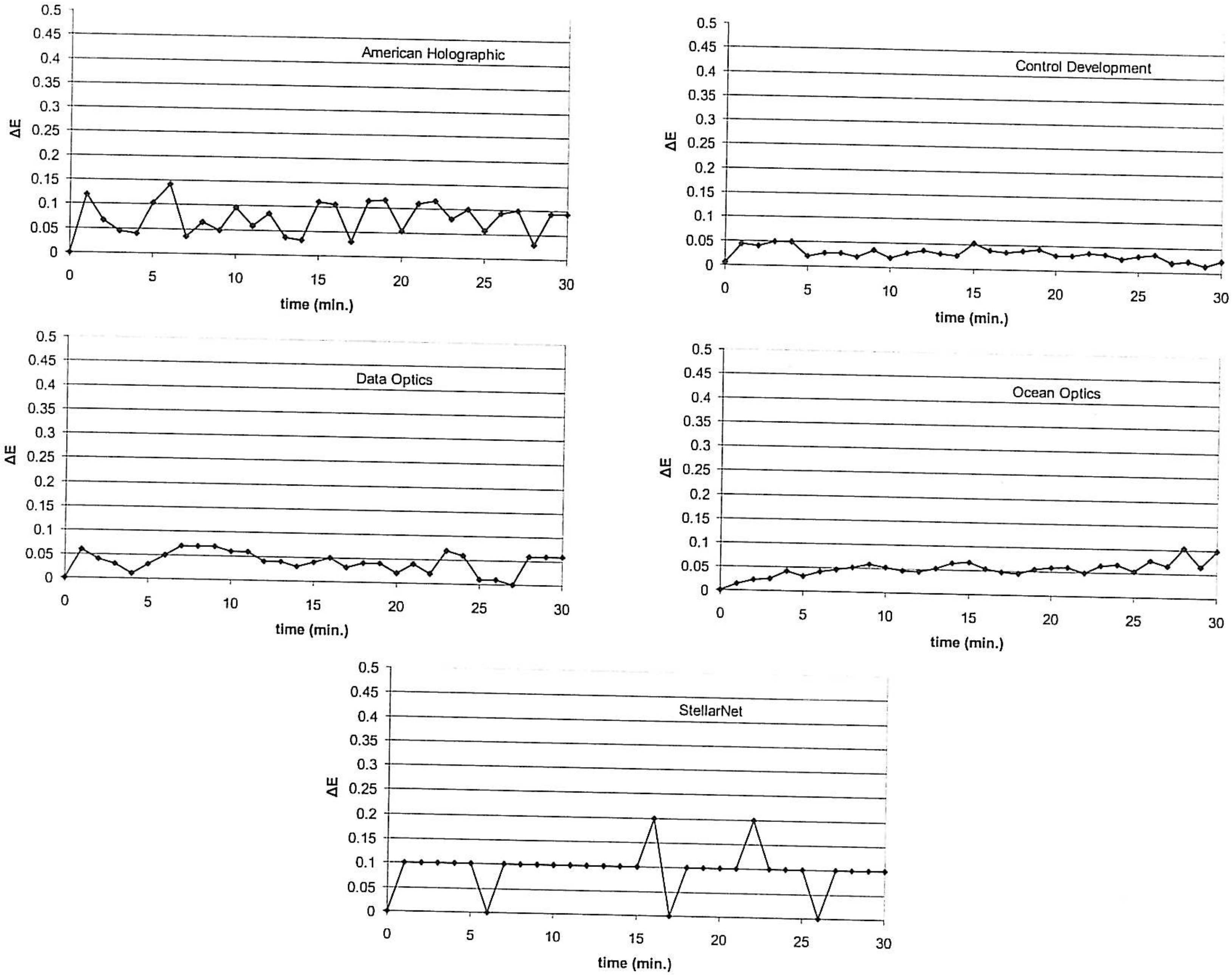

Figure 8a. Stability tests of fading tester with different devices. Color differences recorded over 30 minutes.

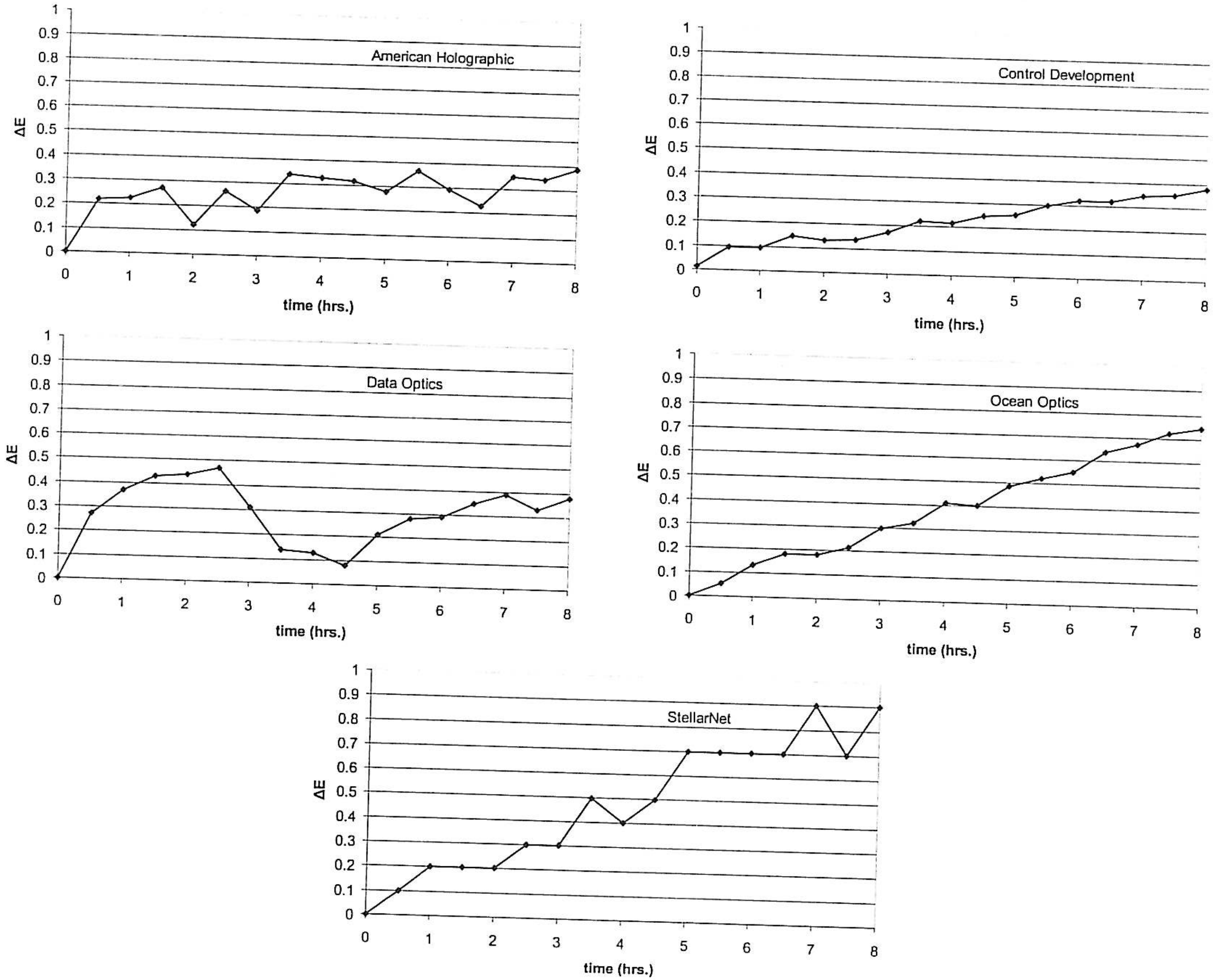

Figure 8b. Stability tests of fading tester with different devices. Color differences recorded over 8 hours.

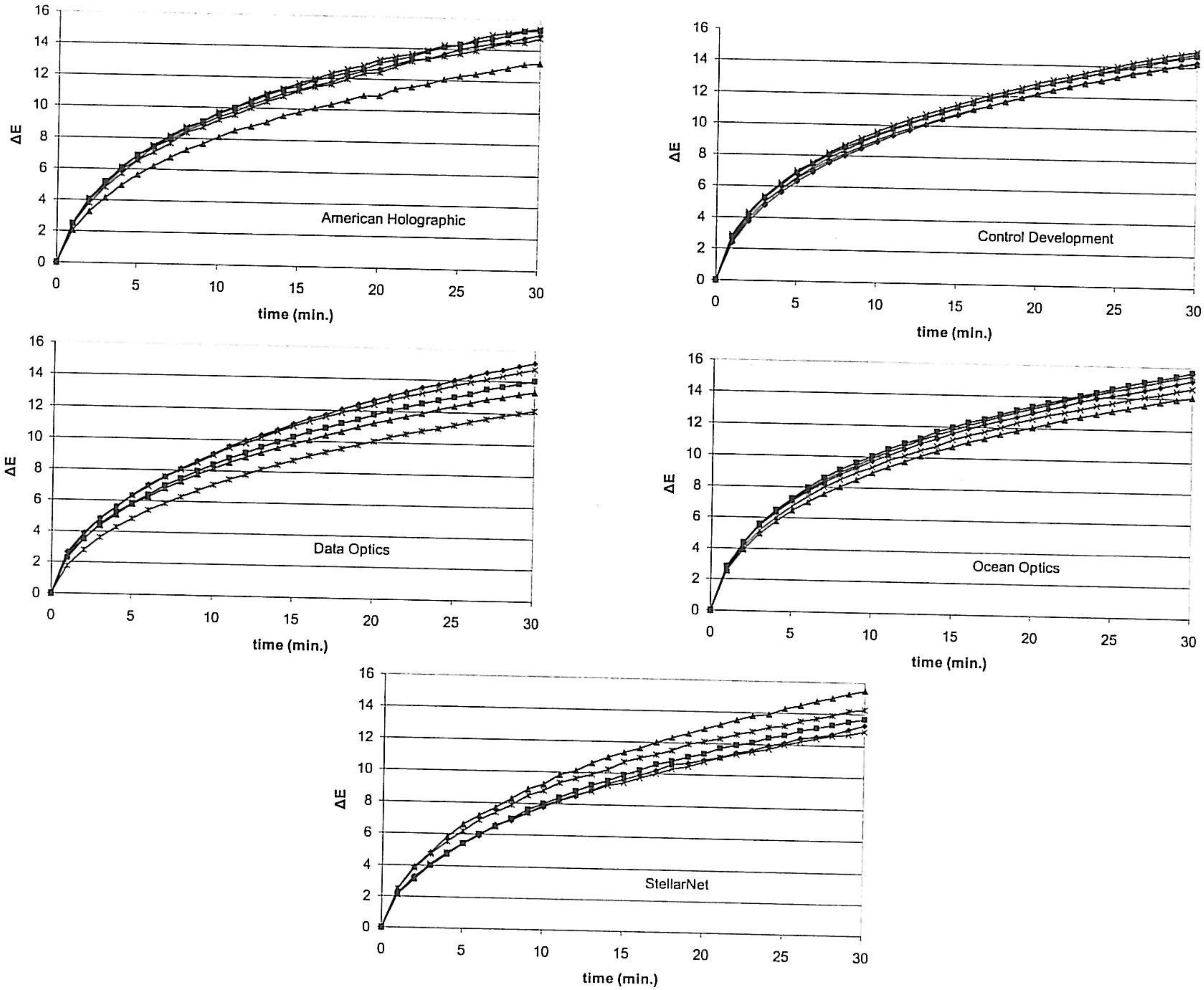

Figure 9a. Fading tests of Blue Wool #1 using each of the five devices as detector.

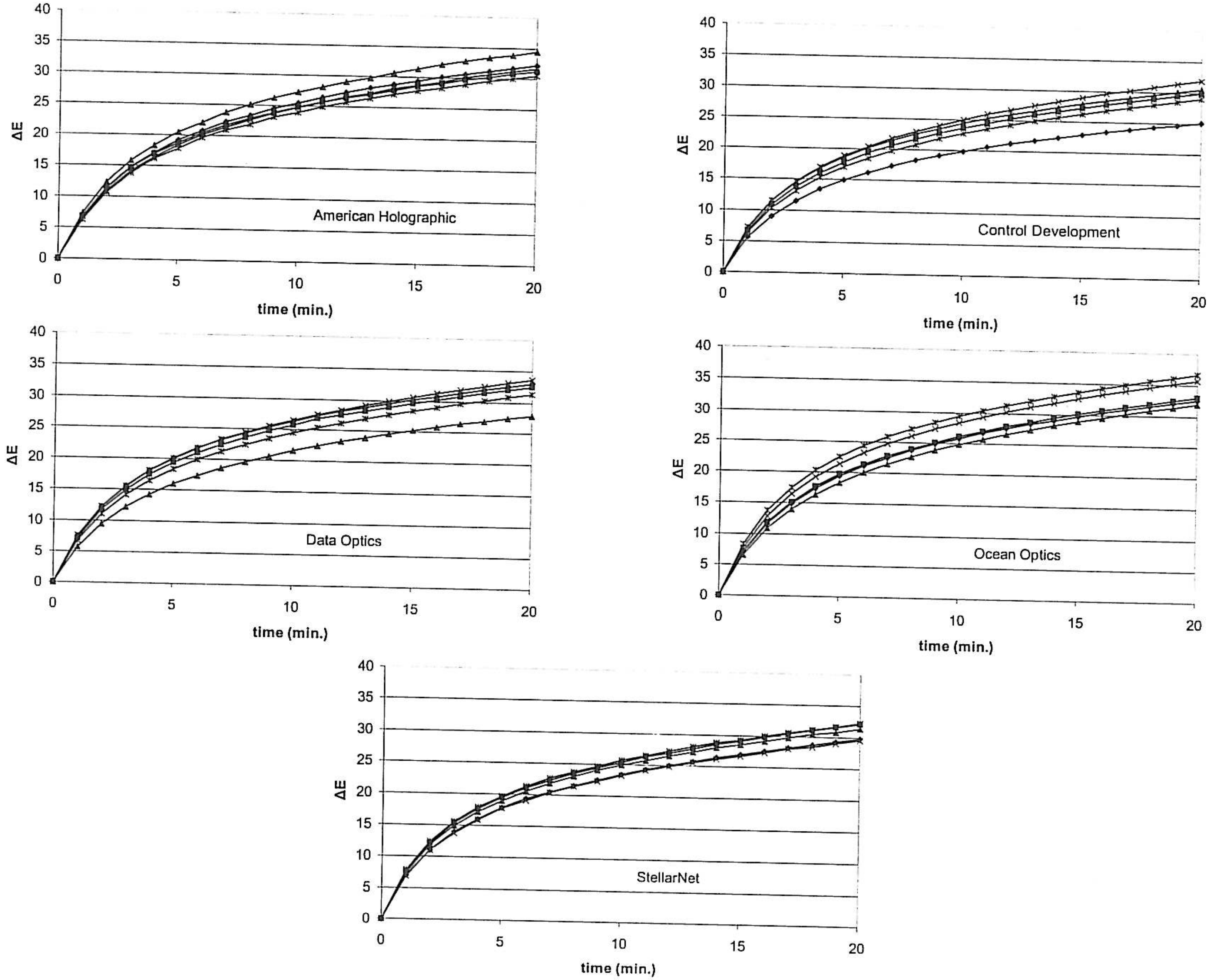

Figure 9b. Fading tests of Bengal Rose gouache on paper using each of the five devices as detector.

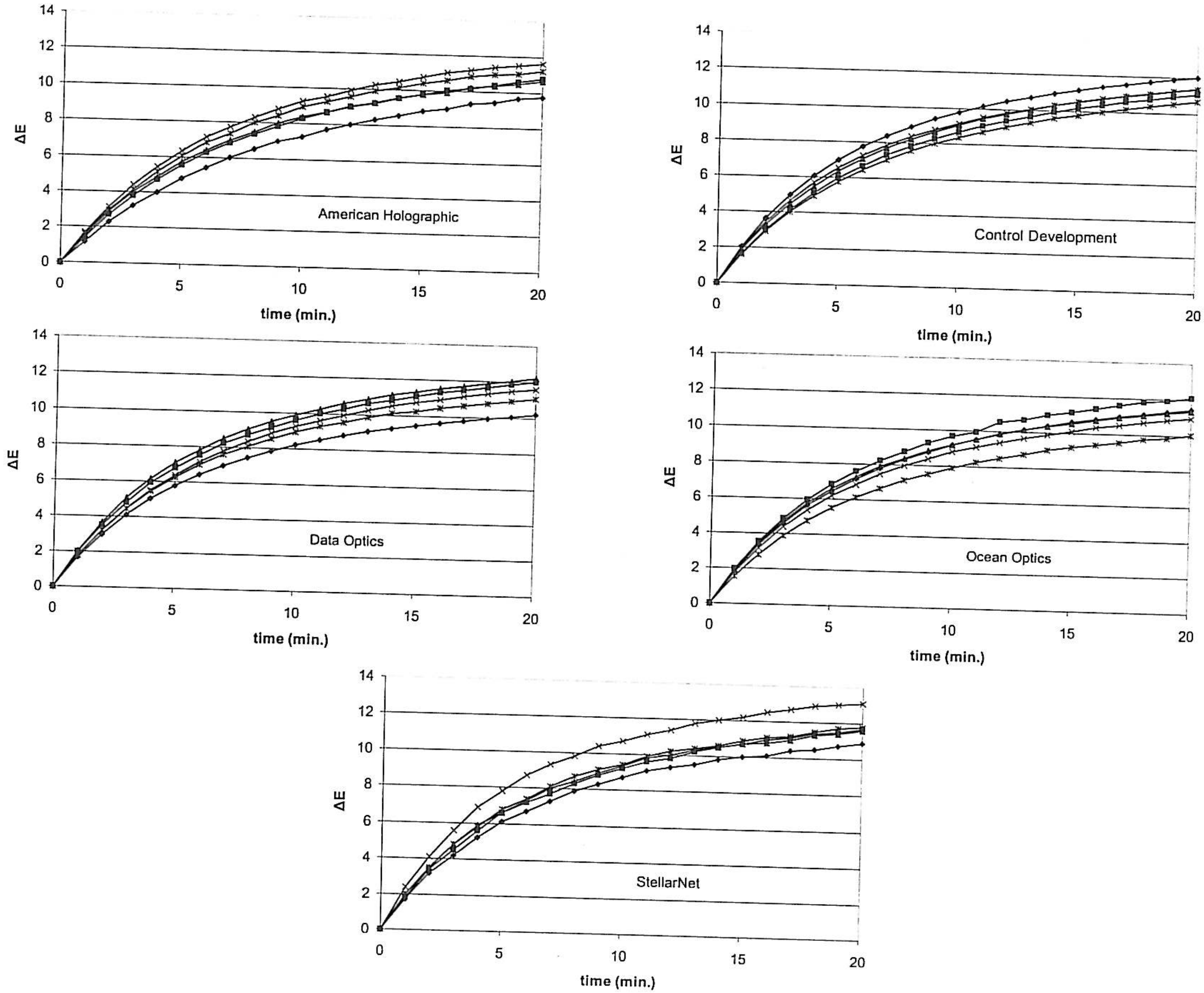

Figure 9c. Fading tests of Geranium gouache on paper using each of the five devices as detector.

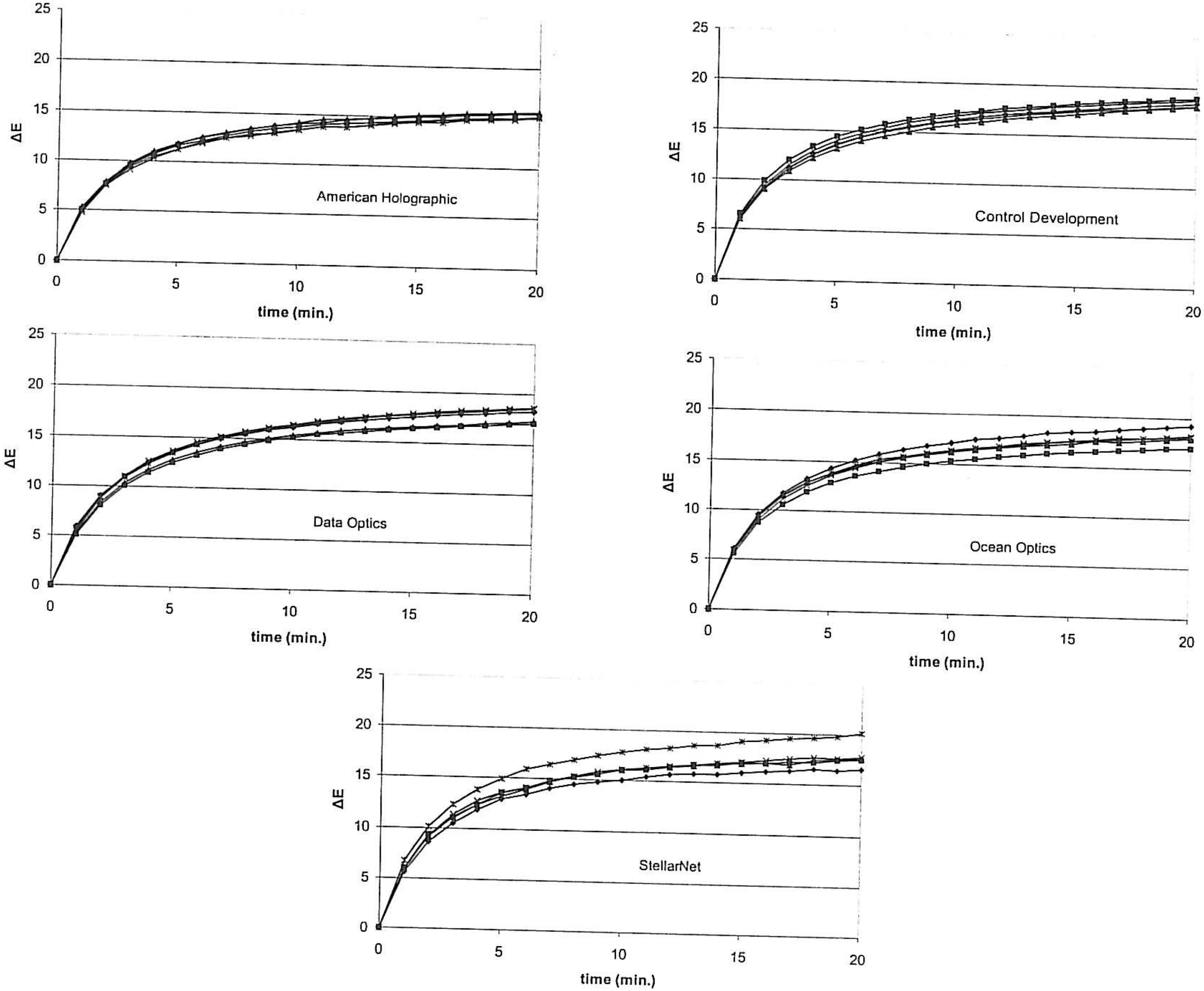

Figure 9d. Fading tests of Magenta gouache on paper using each of the five devices as detector.

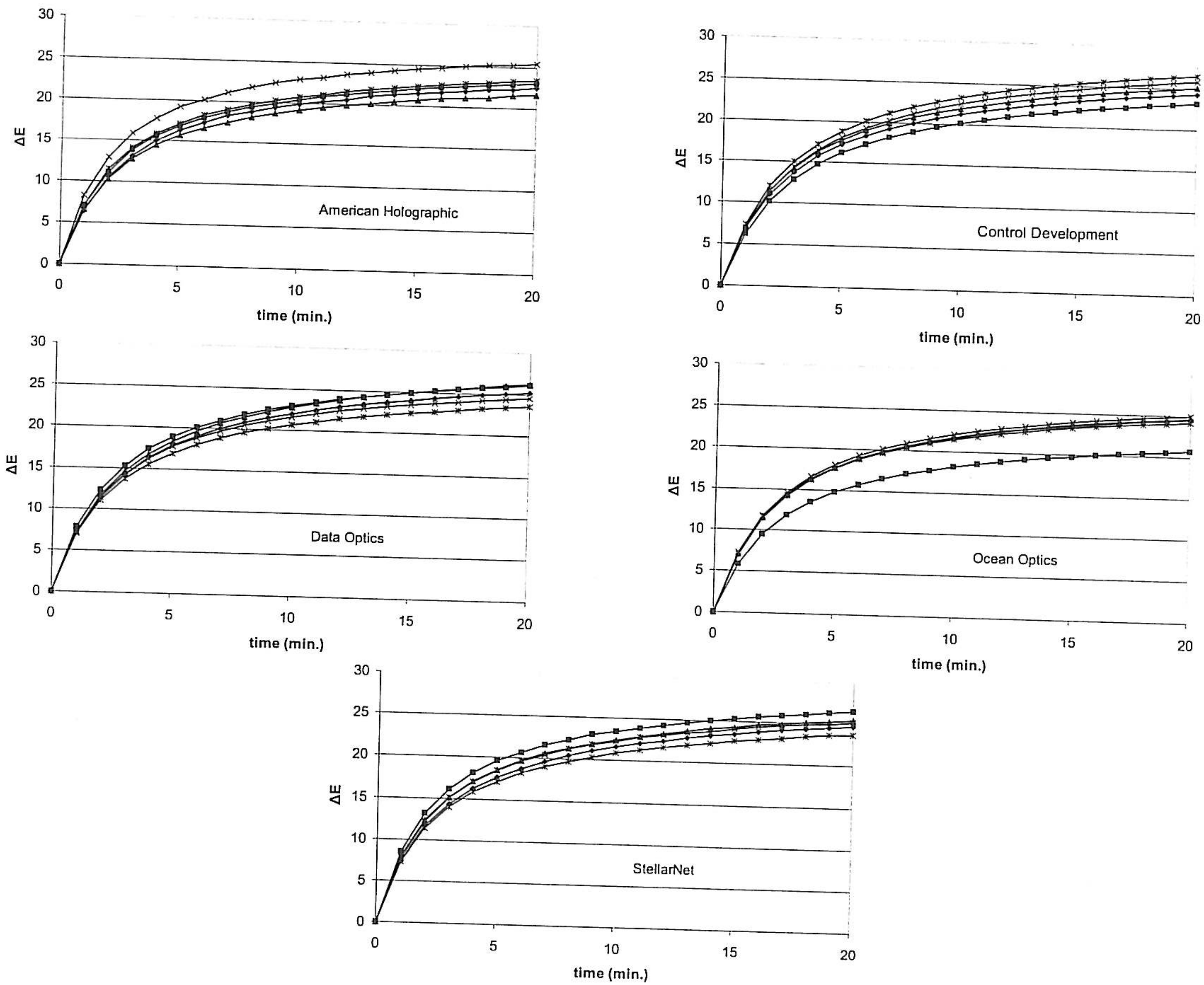

Figure 9e. Fading tests of Rose Malmaison gouache on paper using each of the five devices as detector.

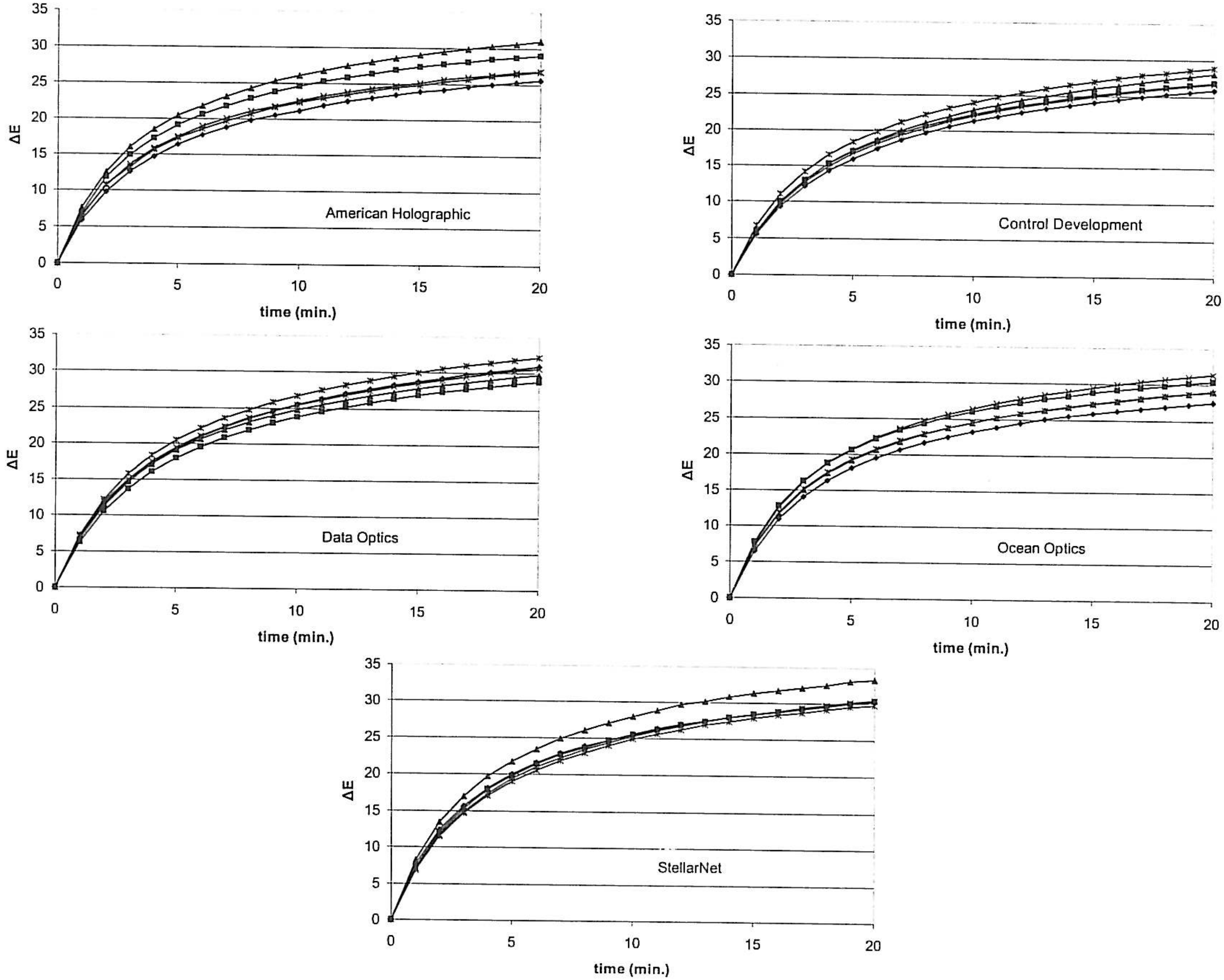

Figure 9f. Fading tests of Rose Tyrien gouache on paper using each of the five devices as detector.

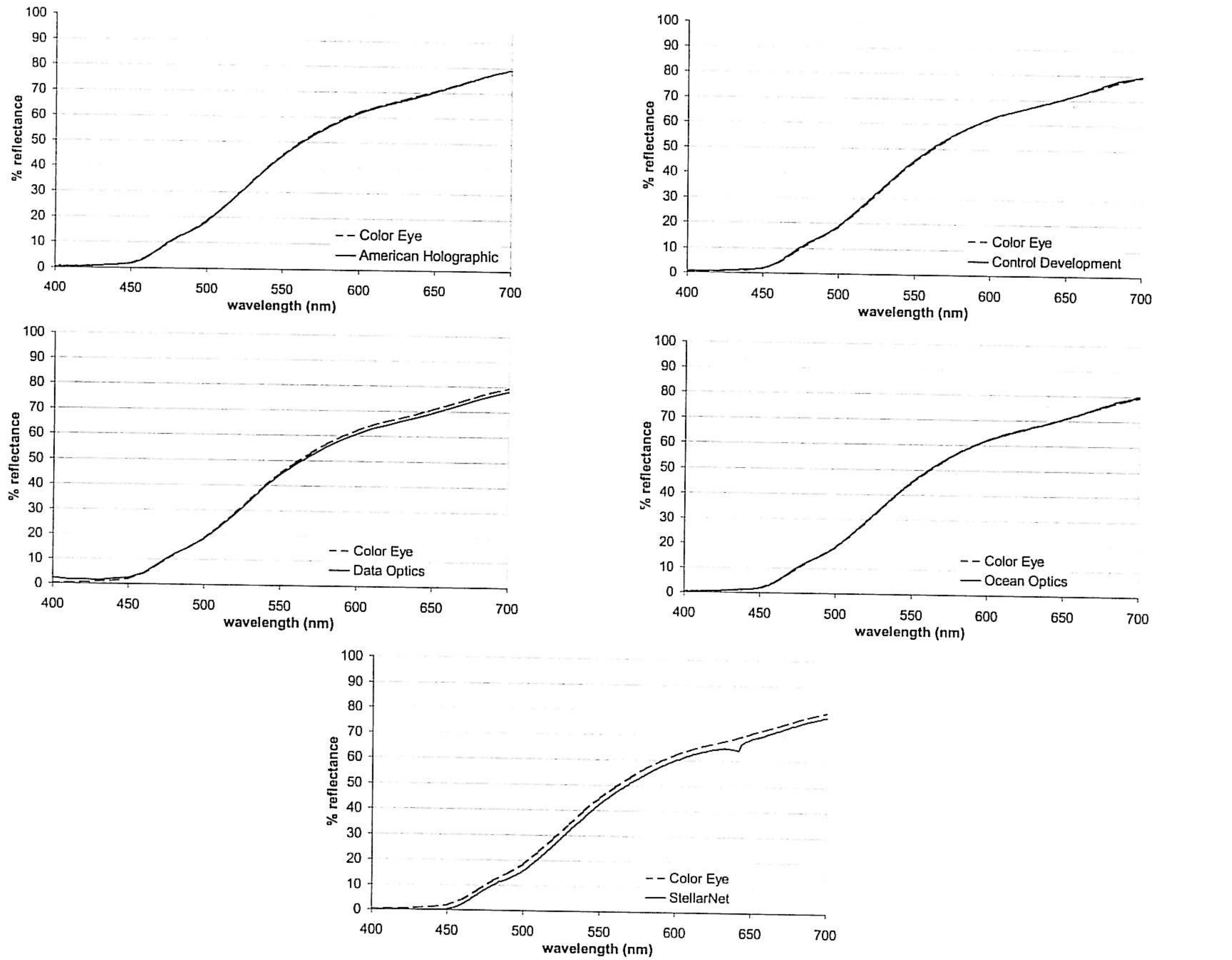

Figure 10. Reflectance spectra of standard white tile when illuminated by low correlated color temperature source, measured with the fading tester using each of the five devices, compared to transmission spectrum of filter, measured on standard spectrometer.

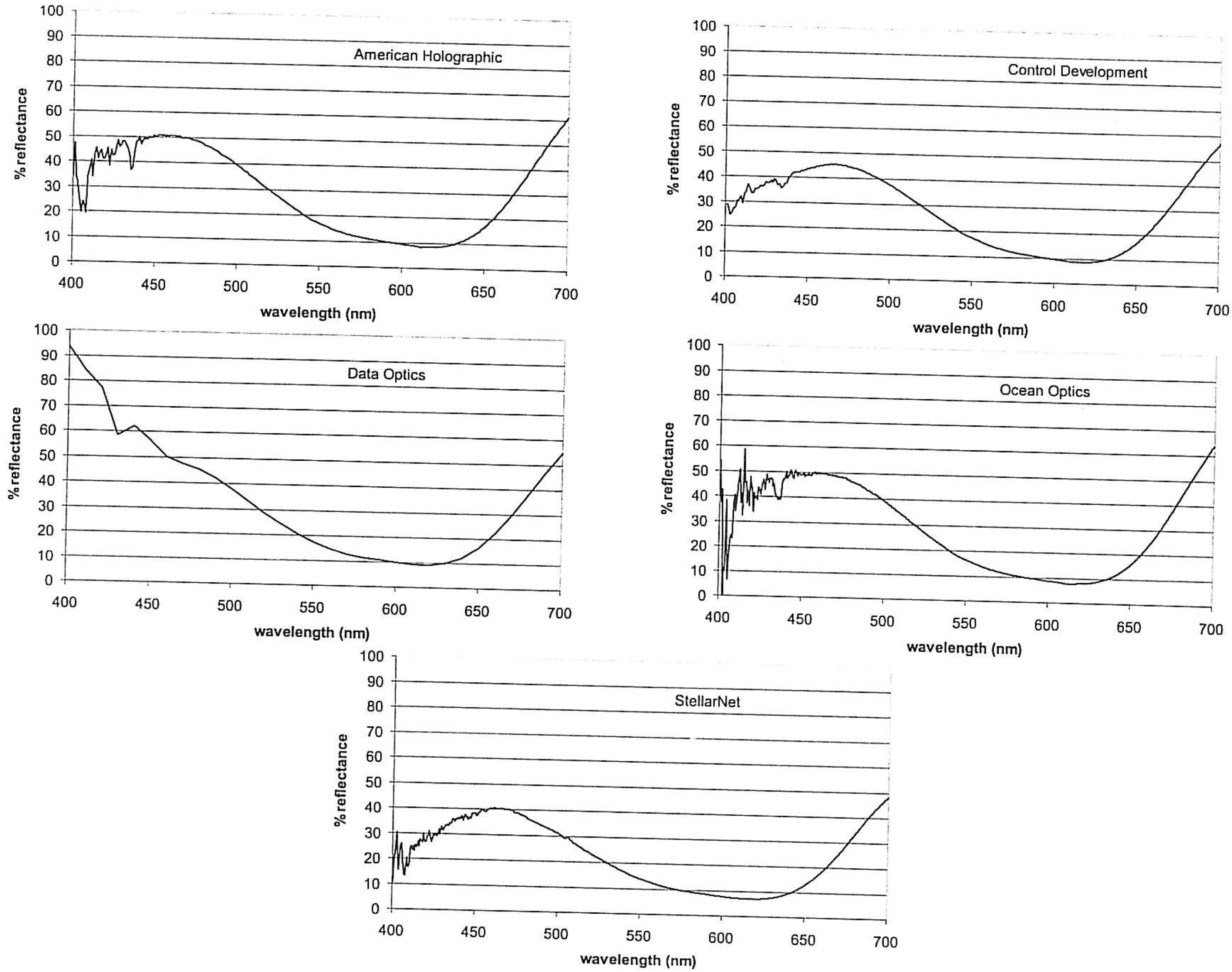

Figure 11. Reflectance spectra of Blue Wool #1 illuminated by low correlated color temperature source, measured with the fading tester using each of the five devices.

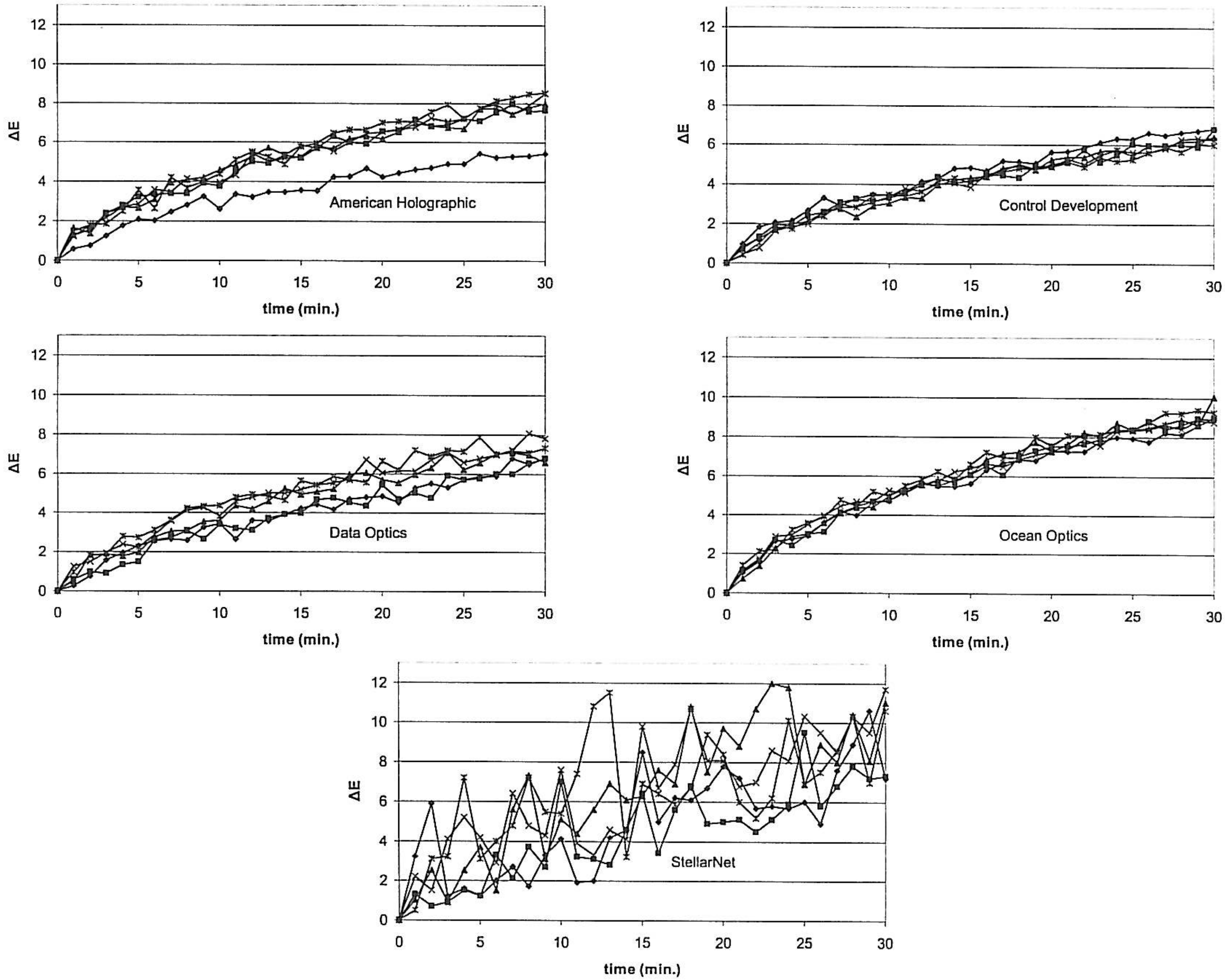

Figure 12. Fading tests of Blue Wool #1 illuminated by low correlated color temperature source, using each of the five devices as detector.